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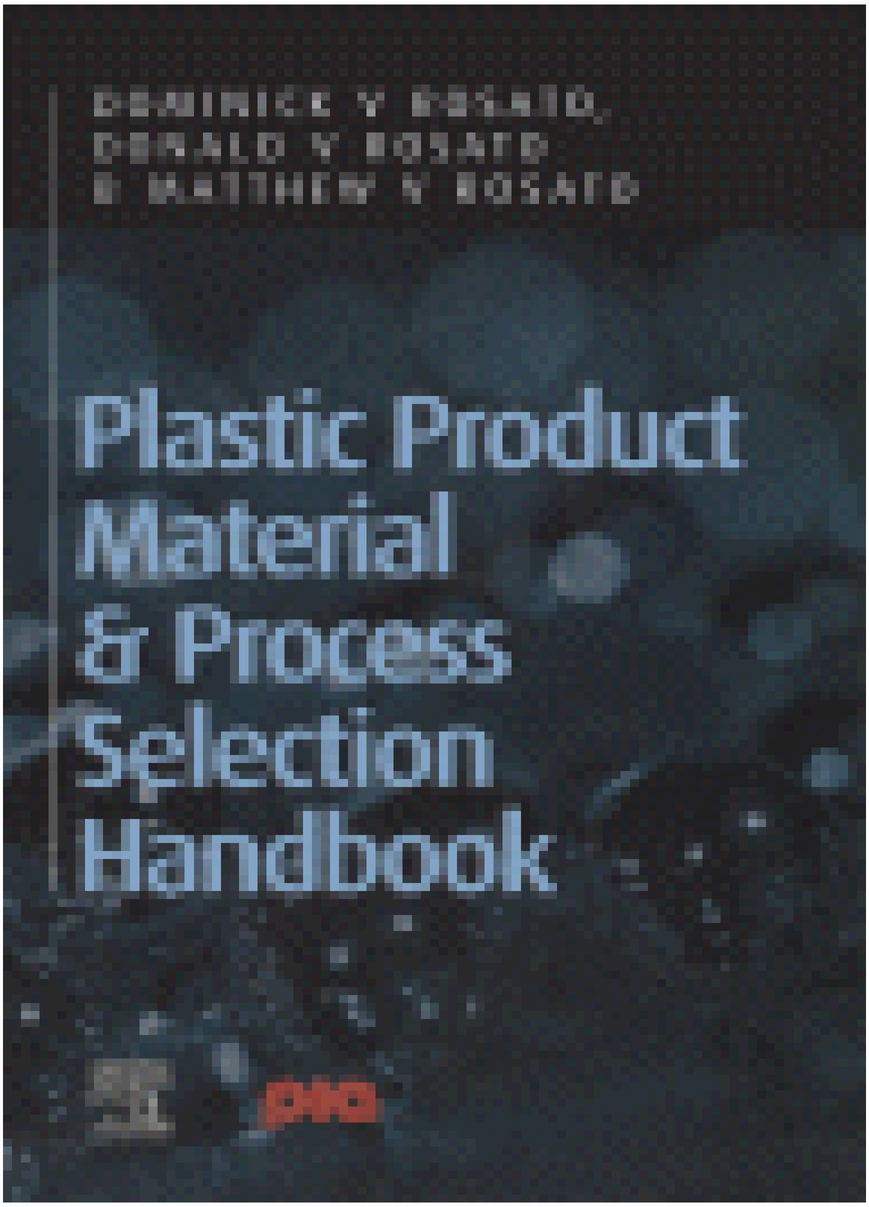
Plastic Product Material and Process Selection Handbook

by Dominick V. Rosato, Donald V. Rosato, Matthew V. Rosato


DOMINICK V ROSATO,
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& MATTHEW V ROSATO
Plastic Product Material & Process Selection Handbook

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Preface, acknowledgement

This book is for people involved or to be involved in working with plastic material and plastic fabricating processes that include those concerned or in departments of material, processing, design, quality control, management, and buyers. The information and data in this book are provided as a comparative guide to help in understanding the performance of plastics and in making the decisions that must be made when developing a logical approach to fabricating plastic products to meet performance requirements at the lowest costs. Information and data can also be used when compromises have to be made in evaluating plastics and processes. The book is formatted to allow for easy reader access and this care has been translated into the individual chapter constructions and index.

This book has been prepared with the awareness that its usefulness will depend on its simplicity and its ability to provide essential information.

The information and data presented in this book are not intended to be used as a substitute for more up-to-date and accurate information on the specific plastics and processes. Such specific details can be obtained from in-house sources, testing laboratories, computer databases, material suppliers, data/information sources, consultants, and various institutions. References in this book represent examples for additional sources of plastics and processes.

This book was written to serve as a useful reference source for people new to plastics as well as providing an update for those with experience. It highlights basic plastic materials and processes that can be used in designing and fabricating plastic products. As with designing any material and/or using any process for plastic, steel, aluminum, wood, ceramic, and so on, it is important to know their behaviors in order to maximize product performance-to-cost efficiency. This book provides information on the behaviors and processing of the different plastics and primary fabricating equipment including upstream and downstream auxiliary equipment. The information is interrelated between chapters so it is best to review more than one chapter to maximize you understanding the behavior of plastic materials and processes.

Designing to meet product performance and cost depends on being able to analyze the many diverse plastics and processes already existing. One important reason for this approach is that it provides a means to enhance the users' skills. It calls for the ability to recognize situations in which certain plastics and processing techniques may be used and eliminate potential problems.

Problems that are reviewed in this book should not occur. As explained they can be eliminated so that they do not effect the product performance when qualified people understand that the problems can exist. They are presented to reduce or eliminate costly pitfalls resulting in poor product performances or failures. With the potential problems or failures reviewed there are solutions presented. These failure/solution reviews will enhance the intuitive skills of those people who are already working in plastics. Cross-referencing of many pertinent behavior patterns is included so one will better understand the advantages and limitations that can develop with improper approaches.

Products reviewed range from toys to medical devices to cars to boats to underwater devices to containers to springs to pipes to buildings to aircraft to spacecraft and so on. The reader's product to be designed and/or fabricated can directly or indirectly be related to plastic materials, fabricating processes, and/or product design reviews in the book.

This book makes very clear the behavior of the 35,000 different plastics with the different behaviors of the hundreds of processes. It concentrates on the important plastics and processes used to fabricate products. The result is a complete logical approach to designing that involves the proper use of materials and fabricating processes.

Information contained and condensed in this book has been collected from many sources. Included is the extensive information assembled from worldwide personal experience, industrial, and teaching experiences of the two authors totaling over a century. Use was also made of worldwide information from industry (personal contacts, material and equipment suppliers, conferences, books, articles, etc.) and major trade associations. For someone to collect this information would require the person having familiarity in the many facets involved in the plastic industry worldwide.

The information contained in this book is not available on the Internet. The Internet contains an extensive amount of useful and important information that can be used but it is reviewed under many different subjects. However it does not contain all the information in this book.

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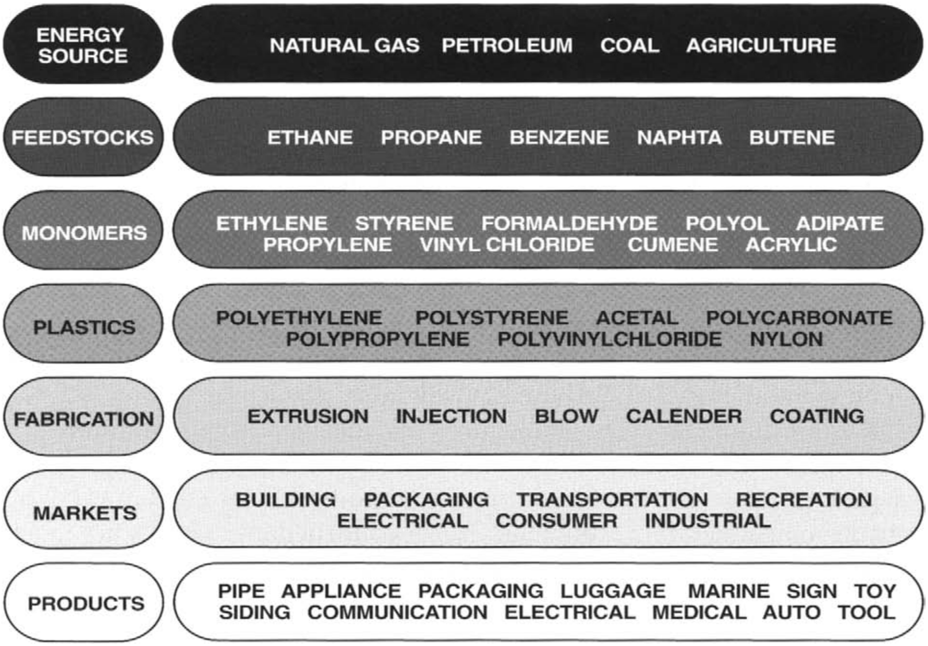
1 INTRODUCTION

Overview

The growth of the plastic industry for over a century has been spectacular evolving into today's routine to sophisticated high performance products. Examples of these products include packaging, building and construction, electrical and electronic, appliance, automotive, aircraft, and practically all markets worldwide. The plastic industry is the fourth largest industry in USA providing 1.5 million jobs. Because of the wide range of products meeting different performance/cost requirements and the large number of materials (35,000) used with different processes, material and process selection can become quite complex if not properly approached as reviewed in this book.

Plastic selection ultimately depends upon the performance criteria of the product that usually includes aesthetics and cost effectiveness. Analyzing how a material is expected to perform with respect to requirements such as mechanical space, electrical, and chemical requirements combined with time and temperature can be essential to the selection process. The design engineer translates product requirements into material properties. Characteristics and properties of materials that correlate with known performances are referred to as engineering properties. They include such properties as tensile strength and modulus of elasticity, impact, hardness, chemical resistance, flammability, stress crack resistance, and temperature tolerance. Other important considerations encompass such factors as optical clarity, gloss, UV stability, and weatherability.[1, 248, 482]

It would be difficult to imagine the modern world without plastics. Today they are an integral part of everyone's life-style, with products varying from commonplace domestic to sophisticated scientific products.[451] As a matter of fact, many of the technical wonders we take for granted would be impossible without versatile, economical plastics. The information in this book reviews the World of Plastics from plastic materials-to-processes that influence product designs that continue to generate the growth of plastics worldwide (Figure 1.1).



ENERGY SOURCE	NATURAL GAS PETROLEUM COAL AGRICULTURE
FEEDSTOCKS	ETHANE PROPANE BENZENE NAPHTA BUTENE
MONOMERS	ETHYLENE STYRENE FORMALDEHYDE POLYOL ADIPATE PROPYLENE VINYL CHLORIDE CUMENE ACRYLIC
PLASTICS	POLYETHYLENE POLYSTYRENE ACETAL POLYCARBONATE POLYPROPYLENE POLYVINYLCHLORIDE NYLON
FABRICATION	EXTRUSION INJECTION BLOW CALENDER COATING
MARKETS	BUILDING PACKAGING TRANSPORTATION RECREATION ELECTRICAL CONSUMER INDUSTRIAL
PRODUCTS	PIPE APPLIANCE PACKAGING LUGGAGE MARINE SIGN TOY SIDING COMMUNICATION ELECTRICAL MEDICAL AUTO TOOL

Figure 1.1 Overview of the plastic industries from source to products that includes plastics and fabrication processes (courtesy of Plastics FALLO)

There have been a number of paradigm shifts in the plastic business model due to market changes. Gone are the days of just buying plastic and fabricating. Now industries want these associated with design collaboration, numerical analysis and virtual prototyping, global specifications, shorter technology life-cycle factors, quick market introduction windows, and product stewardship such as dematerialization and multiple life cycles. Expectations are higher for plastic materials and processes as well. Metals-to-plastic conversions, micro-molded parts, reinforced structural parts, shielded housings, thermoplastic elastomer applications, and parts for harsh environments are making use of a variety of developed plastics and filler systems.

Plastics are a worldwide, multibillion-dollar industry in which a steady flow of new plastic materials, new fabrication processes, new design concepts, and new market demands have caused rapid and tremendous growth. The profound impact of plastics to people worldwide and in all industries worldwide includes the plastics' industry intelligent practical application that range from chemistry to engineering principles established in the past centuries.[1, 482] These materials utilize the versatility and vast array of inherent plastic properties as well as high-speed/low-energy processing techniques. The result has been the development of cost-effective products used worldwide that in turn continue to have exceptional benefits for people and industries worldwide.

Plastics are now among the nations and world's most widely used materials, having surpassed steel on a volume basis in 1983. With the start of this century, plastics surpassed steel even on a weight basis.[1] These figures do not include the two major and important materials consumed, namely wood and construction or nonmetallic earthen (stone, clay, concrete, glass, etc.). Volume-wise wood and construction materials each are possibly about 70 billion ft^3 (2 billion m^3). Each represents about 45% of the total consumption of all materials. The remaining 10% include other materials with plastics being the largest. Plastic materials and products cover the entire spectrum of the world's economy, so that their fortunes are not tied to any particular business segment. Designers are in a good position to benefit in a wide variety of markets: packaging,[52] building and construction, electronics and electrical, furniture, apparel, appliances, agriculture, housewares, luggage, transportation, medicine and health care, recreation, and so on.

Classifying plastic

Plastics are a family of materials such as ceramics and metals. The family of plastics is classified several ways. The two major classifications are thermoplastics (TPs) and thermosets (TSs). Over 90wt% of all plastics used are TPs. The TPs and TSs in turn are classified as commodity or engineering plastics (CP and EP). Commodities such as PEs, PVCs, PPs, and PSs account for over two-thirds of plastic sales. Engineering plastics are characterized with meeting higher and/or improved performances such as heat resistance, impact strength, and the ability to be molded to high-precision standards. Examples are polycarbonate (PC representing at least 50wt% of all EPs), nylon, acetal, etc. Most of the thermoset plastics, as well as reinforced thermoplastics and thermoset plastics, are of the engineering type. Historically, as more competition and/or production occur for certain engineering plastics, their costs go down and they become commodity plastics. Half a century ago the dividing line costwise was about \$0.15/lb; now it is above \$1.00/lb.

There are different types of plastics that are usually identified by their composition and/or performance. As an example there are virgin plastics. They are plastic materials that have not been subjected to any fabricating process. NEAT polymers identify plastics with Nothing Else Added To. They are true virgin polymers since they do not contain additives, fillers, etc. They are very rarely used. Plastic materials to be processed are in the form of pellets, granules, flakes, powders, flocks, liquids, etc. Of the 35,000 types available worldwide there are about 200 basic types or families that are commercially recognized with less than 20 that are popularly used. Examples of these plastics are shown in Table 1.1.

Within these 20 popular plastics there are five major families of thermoplastics that consume about two-thirds of all thermoplastics. They are the low density polyethylenes (LDPEs), high density polyethylenes (HDPEs), polypropylenes (PPs), polystyrenes (PSs), and polyvinyl chlorides (PVCs),

Thermoplastic: Crystalline or Amorphous

There are crystalline and amorphous thermoplastics (TPs). During processing they soften and upon cooling harden into products that are capable of being repeatedly softened by reheating with their morphology (molecular structure) being crystalline or amorphous. Their softening temperatures vary. An analogy would be a block of ice that can be softened (turned back to a liquid), poured into any shape mold or die, then cooled to become a solid again. This cycle repeats. During the heating cycle care must be taken to avoid degrading or decomposition. With some TPs no change or practically no significant property changes occur. However some may have significant changes.

The crystalline plastics (basic polymers) tend to have their molecules arranged in a relatively regular repeating structure such as polyethylene (PE) and polypropylene (PP). This behavior identifies its morphology; that is the study of the physical form or structure of a material. They are usually translucent or opaque and generally have higher softening points than the amorphous plastics. They can be made transparent with chemical modification. Since commercially perfect crystalline polymers are not produced, they are identified technically as semicrystalline TPs. The crystalline TPs normally has up to 80% crystalline structure and the rest is amorphous.

The amorphous plastic is the term used that means formless describing a TP having no crystalline plastic structure. They form no pattern

Table 1.1 Examples of major plastic families

- Acetal (POM)
- Acrylics
  - Polyacrylonitrile (PAN)
  - Polymethylmethacrylate (PMMA)
- Acrylonitrile butadiene styrene (ABS)
- Alkyd
- Allyls
  - Diallyl isophthalate (DAIP)
  - Diallyl phthalate (DAP)
- Aminos
  - Melamine formaldehyde (MF)
  - Urea formaldehyde (UF)
- Cellulosics
  - Cellulose acetate (CA)
  - Cellulose acetate butyrate (CAB)
  - Cellulose acetate propionate (CAP)
  - Cellulose nitrate
  - Ethyl cellulose (EC)
- Chlorinated polyether
- Epoxy (EP)
- Ethylene vinyl acetate (EVA)
- Ethylene vinyl alcohol (EVOH)
- Fluorocarbons
  - Fluorinated ethylene propylene (FEP)
  - Polytetrafluoroethylene (PTFE)
  - Polyvinyl fluoride (PVF)
  - Polyvinylidene fluoride (PVDF)
- Ionomer
- Ketone
- Liquid crystal polymer (LCP)
  - Aromatic copolyester (TP polyester)
- Melamine formaldehyde (MF)
- Nylon (Polyamide) (PA)
- Parylene
- Phenolic
  - Phenol formaldehyde (PF)
- Polyamide (nylon) (PA)
- Polyamide-imide (PAI)
- Polyarylethers
  - Polyaryletherketone (PAEK)
  - Polyaryl sulfone (PAS)
- Polyarylate (PAR)
- Polycarbonate (PC)
- Polyesters
  - Saturated polyester (TS polyester)
  - Thermoplastic polyesters
    - Polybutylene terephthalate (PBT)
    - Polyethylene terephthalate (PET)
  - Unsaturated polyester (TS polyester)
- Polyetherketone (PEK)
- Polyetheretherketone (PEEK)
- Polyetherimide (PEI)
- Polyimide (PI)
  - Thermoplastic PI
  - Thermoset PI
- Polymethylmethacrylate (acrylic) (PMMA)
- Polyolefins (PO)
  - Chlorinated PE (CPE)
  - Cross-linked PE (XLPE)
  - High-density PE (HDPE)
  - Ionomer
  - Linear LDPE (LLDPE)
  - Low-density PE (LDPE)
  - Polyallomer
  - Polybutylene (PB)
  - Polyethylene (PE)
  - Polypropylene (PP)
  - Ultra-high-molecular weight PE (UHMWPE)
- Polyurethane (PUR)
- Silicone (SI)
- Styrenes
  - Acrylic styrene acrylonitrile (ASA)
  - Acrylonitrile butadiene styrene (ABS
  - General-purpose PS (GPPS)
  - High-impact PS (HIPS)
  - Polystyrene (PS)
  - Styrene acrylonitrile (SAN)
  - Styrene butadiene (SB)
- Sulfones
  - Polyether sulfone (PES)
  - Polyphenyl sulfone (PPS)
  - Polysulfone (PSU)
- Urea formaldehyde (UF)
- Vinyls
  - Chlorinated PVC (CPVC)
  - Polyvinyl acetate (PVAc)
  - Polyvinyl alcohol (PVA)
  - Polyvinyl butyrate (PVB)
  - Polyvinyl chloride (PVC)
  - Polyvinylidene chloride (PVDC)
  - Polyvinylidene fluoride (PVF)

whereby their structure tends to form like spaghetti with their molecules going in all different directions These TPs have no sharp melting point and are usually glassy and transparent such as PS and PMMA. Amorphous plastics soften gradually as they are heated. If they are rigid they may be brittle unless modified with certain additives.

Plastics during processing are normally in the amorphous state with no definite order of molecular chains. If TPs that normally crystallize are not be properly quenched (when hot melt is cooled to solidify the plastic) the result is an amorphous or partially amorphous solid state usually resulting in inferior properties. Compared to crystalline types, amorphous polymers undergo only small volumetric changes when melting or solidifying during processing. This action influences the degree of dimensional tolerance that can be met after the heating/cooling process.

As symmetrical molecules approach within a critical distance during melt processing, crystals begin to form in the areas where they are the most densely packed. A crystallized area is stiffer and stronger, a non-crystallized (amorphous) area is tougher and more flexible. With increased crystallinity, other effects occur. As an example, with polyethylene (crystalline) there is increased resistance to creep.

In general, crystalline types of plastics are more difficult (but controllable) to process, requiring more precise control during fabrication, have higher melting temperatures, and tend to shrink and warp more than amorphous types. They have a relatively sharp melting point. That is, they do not soften gradually with increasing temperature but remain hard until a given quantity of heat has been absorbed, then change rapidly into a low-viscosity liquid. If the correct amount of heat is not applied properly during processing, product performance can be drastically reduced and/or an increase in processing cost occurs.

Different processing conditions influence the performance of plastics. For example, the effects of time are similar to those of temperature in the sense that any given plastic has a preferred or equilibrium structure in which it would prefer to arrange itself timewise. However, it is prevented from doing so instantaneously or at least on short notice. If given enough time, the molecules will rearrange themselves into their preferred pattern. Proper heating time causes this action to occur sooner. Otherwise with a fast action severe shrinkage property changes could occur in all directions in the processed plastic products. This characteristic morphology of plastics can be identified by tests. It provides excellent control as soon as material is received in the plant, during processing, and after fabrication.

Liquid Crystalline Polymer
These are self-reinforcing TP liquid crystal polymers (LCPs) with molecules that are rodlike structures in parallel arrays.[301] LCP's densely packed fibrous polymer chains result in high performance plastics. Unlike many high-temperature TPs, LCPs have a low melt viscosity and are thus more easily processed resulting in faster cycle times than those with a high melt viscosity thus reducing processing costs. They have the lowest warpage and shrinkage of all the TPs. When they are injection molded or extruded, their molecules align into long, rigid chains that in turn align in the direction of flow and thus act like reinforcing fibers giving LCPs both very high strength and stiffness. Result is high strength at extreme temperatures, excellent mechanical property retention after exposure to weathering and radiation, good dielectric strength as well as arc resistance and dimensional stability, low coefficient of thermal expansion, excellent flame resistance, and easy processability.

Their high strength-to-weight ratios are particularly useful for weight-sensitive products. Hydrolytic stability in boiling water is excellent. They are exceptionally inert and resist stress cracking in the presence of most chemicals at elevated temperatures, including the aromatic and halogenated hydrocarbons as well as strong acids, bases, ketones, and other aggressive industrial products. High-temperature steam, concentrated sulfuric acid, and boiling caustic materials will deteriorate LCPs. In regard to flammability, LCPs have an oxygen index ranging from 35 to 50%. When exposed to open flame they form an intumescent char that prevents dripping.

Their UL continuous-use rating for electrical properties is as high as 240C (464F). High heat deflection value permits LCP molded products to be exposed to intermittent temperatures as high as 315C (600F) without affecting their properties. Their resistance to high-temperature flexural creep is excellent, as are their fracture-toughness characteristics. This family of different LCPs resists most chemicals and weathers oxidation and flame, making them excellent replacements for metals, ceramics, and other plastics in many product designs.

Thermoset

When processing thermosets (TSs) heat is applied making them flowable. At a higher temperature they solidify and become infusible and insoluble. Cured TSs can not be resoftened with heat. Its curing cycle is like boiling an egg that has turned from a liquid to a solid and cannot be converted back to a liquid. They undergo a crosslinking chemical reaction of its molecules by the action of heat and pressure (exothermic reaction), oxidation, radiation, and/or other means often in the presence of curing agents and catalysts. Their scrap can be granulated and used as filler in TSs as well as TPs. In general, with their tightly crosslinked structure there are TSs that resist higher temperatures and provide greater dimensional stability and strength than most TPs.

Cure A-B-C stages identify their cure cycle where A-stage is uncured, B-stage is partially cured, and C-stage is fully cured. Typical B-stage is TS molding compounds and prepregs, which in turn are processed to produce C-stage fully cured plastic material products (Chapters 14 and 15).

Crosslinked Plastic

Certain TPs can readily be converted to TSs providing improved and/or different properties. Crosslinking is an irreversible change that goes through a chemical reaction. Cure is usually accomplished by the addition of curing (crosslinking) agents with or without heat and pressure. Crosslinking improves resistance to thermal degradation of physical properties and improves resistance to cracking effects by liquids and other harsh environments, as well as resistance to creep and cold flow, among other effects. Prime interest has been with aliphatic polymers such as the olefins that include the polyethylenes and polypropylenes; also popular are polyvinyl chloride. The crosslinked PE, identified as XLPE or PEX, is recognized as a standard within the industry. Use includes electrical cable coverings, cellular materials (foams), rotationally molded articles, and piping.[68, 69]

High-intensity radiation from electron beams or UV (ultraviolet) sources has been used to initiate polymerization in TS systems of oligomers capped with reactive methacrylate (acrylic) groups or isocyanates. Using this crosslinking polymerization technique, films with low shrinkage and high adhesion properties have been used in such applications as pressure-sensitive adhesives, glass coatings, and dental enamels.

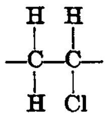
Property and behavior

When designing and/or fabricating a product a specific plastic is used. A type from a plastic producer and/or requirements for a plastic identifies it. The same named, such as low density polyethylene, from two different companies usually has slightly different properties and processing characteristics. Data throughout this book which identifies a plastic such as polyethylene (PE) may differ since literally thousands of PEs are available. These data are presented to provide guides. Data for a specific plastic are available from a plastic producer to the use of databases.

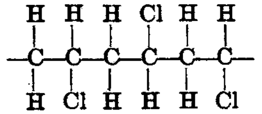
The materials being reviewed in this book, as in the industry, are identified by different terms such as polymer, plastic, resin, elastomer, reinforced plastic (RP), and composite unreinforced or reinforced plastic. They are somewhat synonymous. Polymers, the basic ingredients in plastics, can be defined as high molecular weight organic chemical compounds, synthetic or natural substances consisting of molecules. Practically all of these polymers are compounded with other products (additives, fillers, reinforcements, etc.) to provide many different properties and/or processing capabilities. Thus plastics is the correct technical term to use except in very few applications where only the polymer is used to fabricate products.

They undergo some primary processing such as distillation, cracking, or solvent extraction to produce ethylene (C_2H_4), propylene (C_3H_6), or benzene (C_6H_6) that are precursors to plastics. Chemical composition or the morphology of plastics is basically organic polymers that are very large molecules composed of connecting chains of carbon (C) items generally connected to hydrogen atom elements (H) and often also oxygen (O), nitrogen (N), chlorine (Cl), fluorine (F), and sulfur (S). Morphology is the study of the physical form or structure of a material (thermoplastics crystallinity or amorphous); the physical molecular structures of a polymer or in turn a plastic. As a result of these structures in production of plastics, processing the plastics into products, and product designs, great differences are found in mechanical and other properties.[3, 5, 6, 211, 248]

A polymer is a large molecule built up by a repetition of small simple chemical units. These large molecules are formed by the reaction of a monomer.[72] For example, the monomer for the plastic polyvinyl chloride (PVC) is vinyl chloride. When the vinyl chloride monomer is subjected to heat and pressure it undergoes a process called polymerization (Table 1.3): the joining together of many small molecules in repeat units to make a very large molecule. Structural representations of the monomer repeat unit and polymer are shown below.



Repeat unit



Polymer chain

The number of repeat units in PVC may range from 800 to 1600 that in turn produces different polymers. In some cases a polymer molecule will have a linear configuration, much as a chain is built up from its links. In other cases the molecules are branched or interconnected to form 3-D networks. The particular configuration, which is a function of the plastic materials and manufacturing process involved, largely determines the properties of the finished plastic article.

Even though monomers are generally quite reactive (polymerizable), they usually require the addition of catalysts, initiators, pH control, heat, and/or vacuum to speed and control the polymerization reaction that will result in optimizing the manufacturing process and final product.[74] When pure monomers can be converted directly to pure polymers, it is called the process of bulk polymerization, but often it is more convenient to run the polymerization reaction in an organic solvent (solution polymerization), in a water emulsion (emulsion polymerization), or as organic droplets dispersed in water (suspension polymerization). Often choose of catalyst systems exert precise control over the structure of the polymers they form. They are referred to as stereospecific systems.

There are relatively many different catalysts that are usually used for specific chemical reactions. Types include Ziegler-Natta Catalyst (Z-N), metallocene, and others including their combinations. These systems are available and used worldwide from different companies.[73]

Molecular Structure/Property/Process

Three basic molecular structures or properties affect processing performances (flow conditions, etc.) that in turn affect product performances (strength, dimensional stability, etc.). They are:

1 mass or density (d),
2 molecular weight (MW),
3 molecular weight distribution (MWD)

In crystalline plastics, such as PE, density has a direct effect on properties such as stiffness and permeability to gases and liquids. Changes in density may also affect some mechanical properties. One method of defining plastics melt behavior and property performance is to use information concerning their molecular weight (MW), a reference to the plastic molecules' weight and size. MW is the sum of the atomic weights of all the atoms in a molecule. It represents a measure of the chain length for the molecules that make up the polymer. Atomic weight is the relative mass of an atom of any element based on a scale in which a specific carbon atom (carbon-12) is assigned a mass value of 12. The polymerized polymer contains molecules having many different chain lengths. For some products, the resulting distribution of molecular weights can be calculated statistically and illustrated by the standard form of frequency distribution.

MW of plastics influences their properties. As an example with increasing MW properties increase for abrasion resistance, brittleness, chemical resistance, elongation, hardness, melt viscosity, tensile strength, modulus, toughness, and yield strength. Decreases occur for adhesion, melt index, and solubility.

Adequate MW is a fundamental requirement to meet desired properties of plastics. With MW differences of incoming material, the fabricated product performance can be altered. The more the difference, the more dramatic change occurs in the product. Melt flow rate (MFR) tests are used to detect degradation in products. MFR has a reciprocal relationship to melt viscosity. This relationship of MW to MFR is an inverse one; as one drops, the other increases or visa-versa.

MW refers to the average weight of plastics that is always composed of different weight molecules. These differences are important to the processor, who uses the molecular weight distribution (MWD) to evaluate materials. A narrow MWD enhances the performance of plastic products. Wide MWD permits easier processing. The processing and property characteristics of plastics are partly a function of the MWD that may vary widely, even among plastics of identical composition, density, average molecular weight, and melt index.

Viscosity: Newtonian and Non-Newtonian

The resistance of melt flow exhibited within a body of material identifies its viscosity. It relates to plastic melt flow which in turn relates to the processing behavior of plastic. During melt flow internal friction occurs when one layer of fluid is caused to move in relationship to another layer.[487] Ordinary viscosity is the internal friction or resistance of a plastic to flow. It is the constant ratio of shearing stress to the rate of shear. Shearing is the motion of a fluid, layer by layer, like the movement of a deck of cards.

When plastics flow through straight tubes or channels they are sheared and the viscosity expresses their resistance. A method to measure melt flow is by the melt index (MI) [also called melt flow index (MFI)]. It is an inverse measure of viscosity. High MI implies low viscosity and low

MI means high viscosity. Plastics are shear thinning, which means that their resistance to flow decreases as the shear rate increases. This is due to molecular alignments in the direction of flow and disentanglements.

There is Newtonian and Non-Newtonian viscosity. With Newtonian viscosity the ratio of shearing stress to the shearing strain is constant such as, theoretically, water. In non-Newtonian behavior, which is the case for plastics, the ratio varies with the shearing stress. Such ratios are often called the apparent viscosities at the corresponding shearing stresses. Viscosity is measured in terms of flow in Pas (P), with water as the base standard value of 1.0. The higher the number, the less flow.

Rheology and viscoelasticity

They are a phenomenon of time-dependent in addition to elastic and deformation (or recovery) in response to load. This property possessed by all plastics to some degree, highlights that while plastics have solid-like characteristics such as elasticity, strength, and form-stability, they also have liquid-like characteristics such as flow depending on time, temperature, rate, and amount of loading. Thus, plastics are said to be viscoelastic. The mechanical behavior of these viscoelastic plastics is dominated by such phenomena as tensile strength, elongation at break, stiffness, and rupture energy, which are often the controlling factors in a design. The viscous attributes of plastic melt flow are also important considerations in the fabrication of plastic products.[487]

When discussing melt flow the subject of rheology or flow of matter is involved. It is concerned with the response of plastic melts to mechanical force. An understanding of rheology and the ability to measure rheological properties such as molecular weight and melt flow is necessary before flow behavior can be controlled during processing. Such control is essential for the fabrication of plastic materials to meet product performance requirements.

With plastics there are two types of deformation or flow; viscous, in which the energy causing the deformation is dissipated, and elastic, in which that energy is stored. The combination produces viscoelastic plastics. Not only are there two classes of deformation, there are also two modes in which deformation can be produced: simple shear and simple tension. The actual action during melting, as in the usual screw plasticator is extremely complex, with all types of shear-tension combinations. Together with engineering design, deformation determines the pumping efficiency of a screw plasticator and controls the relationship between output rate and pressure drop through a die system or into a mold.

There is a different flow behavior of plastic when compared to water. The volume of a so-called Newtonian fluid, such as water, when pushed through an opening is directly proportional to the pressure applied following a straight line (flow vs. pressure). The flow rate of a non-Newtonian fluid such as plastics when pushed through an opening increases more rapidly than the applied pressure resulting in a curved line. Different plastics have their own flow rates so that their non-Newtonian curves are different.

This property of viscoelasticity is possessed by all plastics to some degree, and dictates that while plastics have solid-like characteristics, they also have liquid-like characteristics (Figure 1.2). This mechanical behavior is important to understand. It is basically the mechanical behavior in which the relationships between stress and strain are time dependent for plastic, as opposed to the classical elastic behavior of steel in which deformation and recovery both occur instantaneously on application and removal of stress.[1]

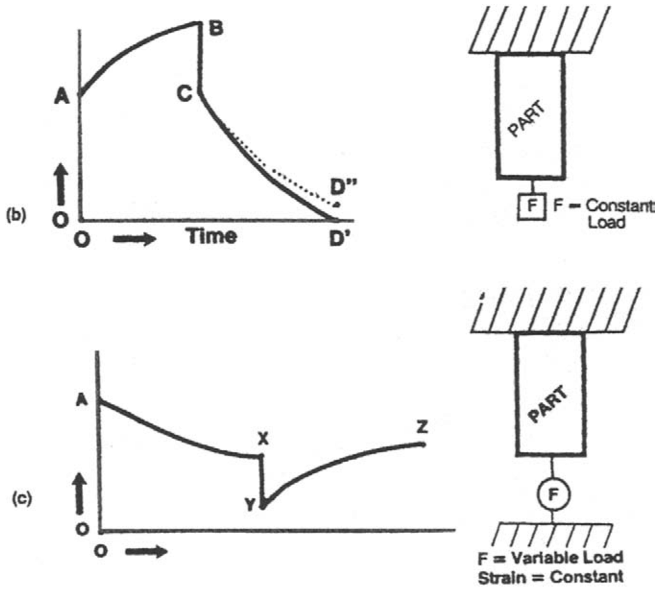


Figure 1.2 Highlighting load-time/viscoelasticity of plastics: (1) stress-strain-time in creep and (2) strain-stress-time in stress relaxation.

Processing and thermal interface

Different plastic characteristics influence processing and properties of plastic products. Table 1.2 reviews these different characteristics that

Table 1.2 Thermoplastic thermal properties are compared to aluminum and steel

*Plastic and (morphology)*ª	*Density, g cm^{-3} (lb ft^{-3})*	*Melt temperature (T_m), °C (°F)*	*Glass transition temperature (T_g), °C (°F)*	*Thermal conductivity, 10^{-4} cal s^{-1} cm^{-1} °C^{-1} (Btu lb^{-1} °F^{-1})*	*Heat capacity, cal g^{-1} °C^{-1} (Btu lb^{-1} °F^{-1})*	*Thermal diffusivity, 10^{-4} cm^2 s^{-1} (10^{-3} ft^2 h^{-1})*	*Thermal expansion 10^{-6} °C^{-1} (10^{-6}*
PP (C)	0.9 (56)	168 (334)	5 (41)	2.8 (0.068)	0.9 (0.004)	3.5 (1.36)	81 (45)
HDPE (C)	0.96 (60)	134 (273)	−110 (−166)	12 (0.290)	0.9 (0.004)	13.9 (5.4)	59 (33)
PTFE (C)	2.2 (137)	330 (626)	−115 (−175)	6 (0.145)	0.3 (0.001)	9.1 (3.53)	70 (39)
PA (C)	1.13 (71)	260 (500)	50 (122)	5.8 (0.140)	0.075 (0.003)	6.8 (2.64)	80 (44)
PET (C)	1.35 (84)	250 (490)	70 (158)	3.6 (0.087)	0.45 (0.002)	5.9 (2.29)	65 (36)
ABS (A)	1.05 (66)	105 (221)	102 (215)	3 (0.073)	0.5 (0.002)	3.8 (1.47)	60 (33
PS (A)	1.05 (66)	100 (212)	90 (194)	3 (0.073)	0.5 (0.002)	5.7 (2.2)	50 (28
PMMA (A)	1.20 (75)	95 (203)	100 (212)	6 (0.145)	0.56 (0.002)	8.9 (3.45)	50 (28
PC (A)	1.20 (75)	266 (510)	150 (300)	4.7 (0.114)	0.5 (0.002)	7.8 (3.0)	68 (38
PVC (A)	1.35 (84)	199 (390)	90 (194)	5 (0.121)	0.6 (0.002)	6.2 (2.4)	50 (128
Aluminum	2.68 (167)	1000		3000 (72.5)	0.23	4900 (1900)	19 (10
Steel	7.9 (493)	2750		800 (21.3)	0.11	1000 (338)	11(6.1)

occur with thermoplastics. Important are glass transition temperature (T_g) and melt temperature (T_m).

The T_g relates to temperature characteristics of plastics that influence the plastic's processability. It is the reversible change in phase of a plastic from a viscous or rubbery state to a brittle glassy state. Below T_g thermoplastic behaves like glass and is very strong and rigid. Above this temperature it is not as strong or rigid as glass, nor is it as brittle as glass. At and above T_g the plastic's volume or length increases more rapidly and rigidity and strength decrease. Most noticeable is a reduction that can occur by a factor of 1,000 in stiffness. The amorphous TPs have a more definite T_g when compared to crystalline TPs. Even with variation it is usually reported as a single value. The T_g generally occurs over a relatively narrow temperature range.

Crystalline plastics have specific melt temperatures (T_m) or melting points. Amorphous plastics do not. They have softening ranges that are small in volume when solidification of the melt occurs or when the solid softens and becomes a fluid type melt. They start softening as soon as the heat cycle starts. Regardless a melting temperature is reported usually representing the average in the softening range.

The T_m is dependent on the processing pressure and the time under heat, particularly during a slow temperature change for relatively thick melts during processing. Also, if the T_m is too low, the melt's viscosity will be high and more costly power required for processing it. If the viscosity is too high, degradation will occur. There is the correct processing window used for the different plastics.

Compounding and alloying

Converting polymers to almost 35,000 plastics includes mechanical mixing/blending one or more polymers with additives, fillers, and/or reinforcement. They do not normally depend on chemical bonds, but do often require special compatibilizers. Mechanical compounding is extensively used (Chapter 5).

Using a post-reactor technique, plastics can be compounded by alloying or blending polymers in addition to using additives such as colorants, flame retardants, plasticizers, biocides, heat or light stabilizers, lubricants, fillers, reinforcements, and/or many more. With combinations of two or more polymers synergistic property improvements beyond those that are purely additive in effect develop. Among the techniques used to combine dissimilar polymers are crosslinking to form what are called interpenetrating networks (IPNs), grafting to improve the compatibility of the plastics, reactive polymerization where molecular structure changes occur.[70–72, 248, 475]

Introduction to property

Throughout this book many different properties are reviewed. What follows is a preliminary that provides some degree of familiarity with the variations of properties existing in plastics. The following Tables 1.3 to 1.6 provide an introduction to a few plastics and some of their properties.

The remainder of this book will provide additional information on many different plastics regarding their diversification of properties, fabricating processes, design behaviors, and markets they serve worldwide.[1, 219, 421] As an example there are plastics to meet different temperatures (Figure 1.3). Figure 1.4 provides a guide and comparison to the temperature capabilities for commodity and engineering plastics as well as steel (tensile yield strength vs. temperature).

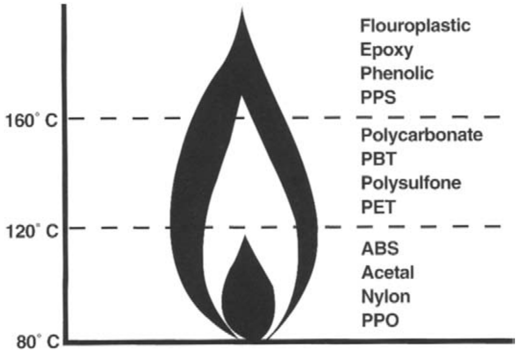


Figure 1.3 Examples of plastics subjected to temperatures

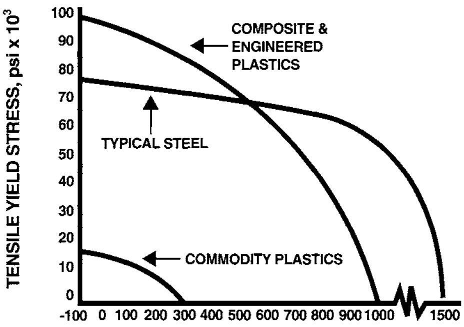


Figure 1.4 Guide on strength to temperature of plastics & steel (courtesy of Plastics FALLO)

Plastic behavior

To understand plastics, one must first appreciate and accept the polymer chemist's ability too literally rearrange the molecular structure of the polymer (that becomes the plastic) to provide an almost infinite variety of compositions that differ in form, melt behavior, thermal behavior, appearance, properties, cost, and other behaviors. One must also approach the subject with a completely open mind that will accept all the contradictions that could make it difficult to pin common labels on the different families of plastics or even on the many various types within a single family that are reviewed in this book. Since each plastic has distinctive characteristics such as performance properties and/or fabricating procedures, they are labeled by their many different behaviors. This section highlights a few of the behaviors. Throughout this book many more behaviors are presented.

Thermal Behavior

In order to select materials that will maintain acceptable mechanical characteristics and dimensional stability one must be aware of both the normal and extreme thermal operating environments to which a product will be subjected. TS plastics have specific thermal conditions when compared to TPs that have various factors to consider which influence the product's performance and processing capabilities. TPs' properties and processes are influenced by their thermal characteristics such as melt temperature (T_m), glass-transition temperature (T_g), dimensional stability, thermal conductivity, specific heat, thermal diffusivity, heat capacity, coefficient of thermal expansion, and decomposition (T_d) Table 1.2 also provides some of these data on different plastics. There is a maximum temperature or, to be more precise, a maximum time-to-temperature relationship for all materials preceding loss of performance or decomposition. Data presented for different plastics in Figure 1.5 show 50% retention of mechanical and physical properties obtainable at room temperature, with plastics exposure and testing at elevated temperatures.

Residence Time

The process of heating and cooling TPs can be repeated indefinitely by granulating scrap, defective products, and so on. During the heating and cooling cycles of injection, extrusion, and so on, the material develops a time at heat history or residence time. With only limited repeating of the recycling, the properties of certain plastics are not

Table 1.3 General properties of thermoplastic

Resin material	Impact strength notched izod, ft-lb/in., ½ in. bar	Tensile strength, psi × 10^3	Tensile modulus, psi × 10^3	Elongation, (%)	Flexural strength, psi × 10^3	Compressive strength, psi × 10^3	Compressive modulus, psi × 10^3	Heat distortion temperature, °F, 264 psi	Heat resistance, continuous °F	Coefficient thermal expansion, in./in.-°C × 10^{-5}	Thermal conductivity, cal/cm²-sec-°C-cm × 10^{-4}	Volume resistivity, ohm-cm
Acetal	1.2–2.3	8.8–10	400–410	12–75	13–14	18	410	255	185	8.1–8.5	1.6–5.5	1–10^{14}
ABS	1.0–9.5	3.5–10.5	200–450	10–100	5–15	5–11	200–450	185–230	160–235	5.7–10	5–8	10^{16}–10^{17}
Acrylic	0.4	8.7–10.5	380–430	3–6	14–16	14–17	350–430	167–198	130–200	5–8.5	4.4	>10^{14}
Acrylic high impact	0.5–2.3	5.5–8	225–330	23–38	8.5–12	7–12	250–360	169–190	140–195	6.5–10.5	4.0	10^{16}–10^{17}
Cellulose acetate	.5–5.6	2.3–8.1	—	10–70	2.2–11.5	2.2–10.9	—	111–195	140–175	8–16	4–8	10^{10}–10^{13}
Cellulose acetate butyrate	0.8–6.3	2.6–6.9	—	40–88	1.8–9.3	2.1–9.4	—	113–202	140–175	11–17	4–8	10^{10}–10^{12}
Cellulose propionate	0.9–10.2	1.8–7.3	—	30–100	2.8–11	3–9.6	—	121–228	140–175	11–16	4–8	10^{12}–10^{16}
Chlorinated polyether	0.4	6	160	60–160	5	—	130	185–210	250–275	8	3.13	1.5×10^{16}
Chlorotrifluoroethylene	3.5	6	150–190	60–190	8–10	6–12	180	160–170	390	5–7	4–6	10^{18}
Ethyl cellulose	1.7–6	2.3–6.5	—	10–40	3–6.7	—	—	150–200	140–180	10–20	3.8–7	—
Ethyl vinyl acetate	No break	20–40	3.0–15	500–1500	—	—	—	—	120–170	10–20	8	—
FEP	No break	2–3.2	60–80	350	—	—	70	124	400	8.3–10.5	5.9	>10^{18}
Nylon 6	0.9–4	9.5–12.4	200–450	25–300	9–16.6	4–11	347	150–175	250	8.3	5.9	3.3^{12}–4.5^{13}
Nylon 6/6	0.9–2	11.2–13.1	410–480	60–300	14.6	5–13	400	200	250	10	5.8	10^{14}–10^{15}
Nylon 6/10	—	7–8.5	160–280	50–300	10.5	4–6	—	145	220	10	5.5	4.5×10^{13}
Polyallomer	1.5–12	2.9–4.2	100–170	400–650	4–5	—	—	115–140	250	8–11	2–4	>10^{16}
Polycarbonate	2–3	8–9	345	75	11–13.5	12.5	345	270	250–270	7	4.6	2.1×10^{16}
Polyethylene low density	No break	1–2.4	14–38	20–800	—	—	—	—	140–175	10–20	8	10^{15}–10^{18}
Polyethylene medium density	No break	1.7–2.8	50–80	80–600	—	—	—	—	150–180	10–20	8	10^{15}–10^{18}
Polyethylene high density	0.5–23	2.8–5	75–160	10–800	1–4	0.8–3.6	50–110	110–125	180–250	10–20	8	6×10^{15}–10^{18}
Polyethylene high molecular weight	>20	5.4	102	525	3.5	2.4	110	120	250	13	8	>10^{16}
Polypropylene	0.5–15	2.3–5	150–250	10–700	4.5–6	6–8	—	140–200	250	6–8.5	2.8–4	6.5×10^{16}
Polystyrene	0.25–0.65	5–9	400–500	1–2.5	7–15	11.5–16	300–560	167–203	150–180	6–8	1.9–3.3	10^{17}–10^{21}
Polystyrene high impact	0.7–1.5	3.5–8	300–400	10–40	5.5–12.5	8–16	—	150–200	120–170	6.5–8.5	1–3	10^{12}–10^{17}
Polyurethane	No break	4.5–8	—	100–600	0.7–1	20	—	—	150–180	10–20	5	2–10^{14}
Poly(vinyl chloride) (flexible)	Varied	1–4	—	100–450	—	—	—	—	—	7–25	3–4	10^{11}–10^{16}
Poly(vinyl chloride) (rigid)	0.4–22	6–9	200–600	5–40	8–15	10–11	300–400	140–175	160–165	5–10	3–5	10^{12}–10^{16}
Poly(vinyl dichloride) (rigid)	0.8–6.3	7.5–8.8	348–450	65	14.2–17	—	—	212–220	185–210	7–8	3–4	10^{15}
Styrene acrylonitrile (SAN)	0.3–55	10–12	500	1–3.2	17	15–17.5	650	200–208	—	7	3	10^{15}
TFE fluorocarbon	No break	2–5	50–100	75–400	—	4–1.2	70–90	132	550	5.5(25–60°C)	6	>10^{18}

Resin material	Dielectric constant, 60 cycles	Delectric strength, ST ⅛-in. thickness, volts/mil	Power factor, 60 cycles	Arc resistance, sec	Water absorption, 24 hr, %	Rockwell hardness	Flammability, in./min	Specific gravity	Mold shrinkage, in./in.	Clarity
Acetal	3.7–3.8	500	.004–.005	129	0.12–0.25	M94, R120	1.1	1.410–1.425	.022	Translucent to opaque
ABS	2.6–3.5	300–450	.003–.007	45–90	0.2–0.4	R50–120	1.0–2	1.01–1.07	.003–.007	Opaque
Acrylic	3.7	450–500	.04–.05	No tracking	0.3	M84–97	0.6–0.7	1.18–1.18	.002–.006	Transparent
Acrylic high impact	3.5–3.7	450–480	.04–.05	No tracking	0.2–0.3	M20–67	1.1–1.2	1.11–1.18	.004–.008	Translucent to opaque
Cellulose acetate	3.5–7.5	290–600	.01–.06	50–130	2.1–4.2	R35–118	0.5–2	1.23–1.34	.001–.007	Transparent
Cellulose acetate butyrate	3.5–6.4	250–400	.01–.04	—	0.9–2.2	R31–116	0.5–1.5	1.15–1.22	.003–.006	Transparent
Cellulose propionate	3.4–4.2	300–450	.01–.04	170–190	1.2–2.8	R15–120	0.5–1.5	1.16–1.23	.001–.006	Transparent
Chlorinated polyether	3	400	.01	—	.01	R100	Self-ext.	1.4	.004–.006	Semitranslucent to opaque
Chlorotrifluoroethylene	2.65	450	.015	>360	Nil	R85–112	Nil	2.90–2.14	.010–.015	Transparent to opaque
Ethyl cellulose	—	—	—	—	1.3–1.5	R50–110	—	1.11–1.13	—	Transparent to opaque
Ethyl vinyl acetate	2.3	—	—	—	<.01	R3–7	Slow burning	0.93–0.95	.01–.02	Transparent
FEP	2.1	500	.0002	>165	<.01	—	Nonflam.	2.14	.03	Transparent to opaque
Nylon 6	6.1	300–400	0.4–0.6	140	1.5	R107–119	Self-ext.	1.13–1.14	.007–.011	Transparent to opaque
Nylon 6/6	3.6–4.0	300–400	.014	140	1.3	R118-123	Self-ext.	1.13–1.15	.007–.015	Transparent to opaque
Nylon 6/10	4.0–7.6	300–400	.04–.05	140	0.4	R111	Self-ext.	1.07–1.09	.015	—
Polyallomer	3.2	500–1000	.0001–.0005	—	<.01	R50–85	Slow burning	0.90–.906	.01–.02	Transparent to opaque
Polycarbonate	3.17	400	.0009	120	15	M80, R118	Self-ext.	1.2	.005–.007	Transparent
Polyethylene low density	2.28	450–1000	.0001–.0005	Melts	<.02	R10	Slow burning	.910–.925	.01–.03	Transparent to opaque
Polyethylene medium density	2.3	450–1000	.0001–.0005	Melts	<.02	R15	Slow burning	.926–.940	.01–.035	Transparent to opaque
Polyethylene high density	2.3	450–1000	.0001–.0005	Melts	<.01	R30–60	Slow burning	0.94–0.98	.01–.04	Translucent to opaque
Polyethylene high molecular weight	2.3	710	.0003	—	<.01	R55	Very slow	0.94	.03	Translucent to opaque
Polypropylene	2.1–2.27	450–1000	.0001–.0005	13–185	<.01	R30–99	Slow burning	0.90–.0908	.008–.025	Translucent to opaque
Polystyrene	2.5–2.65	500–700	.0001–.0005	60–100	.03–.05	M60–80	0.5–2.5	1.05–1.06	.002–.006	Transparent
Polystyrene high impact	2.5–3.5	500	.003–.005	60–90	.05–.10	M25–69	0.5–2.5	1.04–1.06	.003–.005	Translucent to opaque
Polyurethane	6.7–7.5	450–550	.015–.017	—	0.60–0.80	M28, R60	Slow burning	1.20–1.26	.008–.012	Translucent to opaque
Poly(vinyl chloride) (flexible)	5–9	300–1000	.08–.15	—	0.15–0.75	—	Self-ext.	1.15–1.80	.002–.004	Transparent to opaque
Poly(vinyl chloride) (rigid)	3.4	425–1040	.01–.02	—	.07–.40	R100–120	Self-ext.	1.33–1.58	—	Transparent to opaque
Poly(vinyl dichloride) (rigid)	—	1200	—	—	0.11	R118	Self-ext.	1.50–1.54	.007–.008	Translucent to opaque
Styrene acrylonitrile (SAN)	2.8–3	400–500	—	—	0.23–0.28	M30–83	0.47–0.7	1.07–1.08	.003–.004	Transparent
TFE fluorocarbon	2.1	400	<.0001	No tracking	.01	R58	Nonflam.	2.13–2.18	.02–.06	Transparent to opaque

Table 1.4 General properties of thermoset plastic

Resin material	Impact strength, izod ft-lb/in.	Tensile strength, psi$\times10^3$	Flexural strength, psi$\times10^3$	Flexural modulus, psi$\times10^3$	Compressive strength, psi$\times10^3$	Heat distortion °F@264 psi	Heat resistance, continuous °F	Thermal expansion in./°C$\times10^{-5}$	Thermal conductivity, cal/sec-cm^2-°C-cm$\times10^{-4}$
Alkyd glass-filled general purpose	1.5–4	5–9	12–18	1700–2000	21–29	>400	300	2–5	10–15
Alkyd-glass MAI 30	3–4	7–9	14–19	2000	22–24	>400	350	2–4	10–15
Alkyd-glass MAI 60	8–10	5–9	12–20	2000–2500	24–36	>400	300	2–5	8–12
Alkyd mineral	.30–.35	3–8	6–15	2200–3000	16–20	350–400	275–400	2–5	15–25
DAP glass MIL–M–19833 GDI–30	6–15	7–9.5	17–19	1250–1600	24–45	390–500	365–465	2.7–3.5	6–8
DAP mineral (MDG) MIL–M–14F MIL–P–4389	.28–.40	5.5–6.5	9.6–10	1200	22–25	300–320	350–440	3.5–4.2	13.7
DAP orlon MIL–F–14F SD 1–5	.55–4.5	6.8	9–10.5	710	20–30	240–266	300–350	4–5.4	6.3–6.9
DAP glass MIL–M–14F SDG	0.4–1.2	6.7–9.2	10–19	1300	25–30	350–500	365–465	1.2–3.5	6.7
DAP unfilled	0.3	4	7–9	600	22–24	310	350	—	—
Epoxy glass	5.5	11.5	22	3000–3200	30–38	500	300–500	1.08–1.2	8.5
Epoxy mineral	0.35–0.5	6–11	19.5	900–1200	37	260–360	550	3.7	18.1
Melamine cellulose	.25–.35	5–10	10–16	1300–1600	25–24	350–410	210	2–5.7	7–10.1
Melamine cloth	.55–.90	7–10	12–15	1600	30–35	310	250	2.5–3	10.6
Melamine glass MMI 30	4–16	6–10	15–24	2400	20–32	400	300–400	1.2–2	11.5
Phenolic asbestos MFA 30	3.7	8	16	2500	24	400	450	.5–1	14
Phenolic cloth CFI–10	1.05–2.2	6.5–7	0.5–10	1000–1200	20–25	300–360	275	2–3	9.3
Phenolic cloth CFI–20	2.3	6.5–7.5	10–12.5	1000	22–25	300	340	1.5–3	7
Phenolic flock/flour	.34–.50	6–9	7–12	1000	20–30	270–325	300	2–3.9	7–8
Phenolic glass	9–17	7–11	13.5–22	3000	14–35	600	325–450	.8–1.6	9.7
Phenolic GP	.26–.38	6–9	7–12	1000	25–35	275–370	300	3–4.1	5–8.1
Phenolic GPI–100	13	16.8	24.9	2865	39	>550	—	—	32
Phenolic nylon	0.5	8	12	600	24	290	275	7.5	7.50–18
Phenolic rubber/flour	0.5	4	5.5–7	400	16–18	250	275	1.5–4	5
Urea cellulose	.24–.35	5–10	10–18	1300–1600	25–38	266–380	170	2.7	7–10.1
Silicone	8–20	4–8	13–19	2100–2500	10–13	>900	450–700	.8	7.5
Silicone mineral	.25–.39	2.5–4.4	6.8–8	1250–2270	11–18	340–900	400–700+	2.5–6	4–10

Resin material	Power factor, 60 cycles	Arc resistance, sec	Water absorption %-24 hr	Rockwell hardness	Specific gravity	Mold shrinkage, in./in.	Volume resistivity, ohm/cm	Dielectric constant, 60 cycles	Dielectric strength, STI/8V.P.M.
Alkyd glass-filled general purpose	.01–.02	180+	.07–.2	—	1.93–2.32	.003–.006	1×10^{16}	6.7	275–375
Alkyd-glass MAI 30	.005–.01	180+	.05	—	2.3	.001–.005	—	6	350
Alkyd-glass MAI 60	.020–.030	180+	.07–.10	—	2.02–2.13	.001–.004	10^{12}–10^{14}	5–5.6	375
Alkyd mineral	.030–.045	180+	.05–.12	E108	2.17–2.24	.004–.007	10^{12}–10^{14}	5.7–6.3	375
DAP glass MIL–M–19833 GDI–30	.010–.017	130–180	.05–.25	M108	1.57–186	.0009–.004	10^{15}	4.5	350–400
DAP mineral (MDG) MIL–M–14F MIL–P–4389	.06–.40	140	.2–.5	M100	1.58–1.74	.004–.008	10^{16}+	5.2	350–450
DAP orlon MIL–F–14F SD 1–5	.025–.035	115	.1–.2	M108	1.31–1.34	.009–.010	1×10^{16}	3.8	366–400
DAP glass MIL–M–14F SDG	.010–.017	125–180	.05	E80	1.6–1.75	.002–.004	10^{13}	4.25	420
DAP unfilled	.008	120	.09	M114–116	1.27	.007	2×10^{16}	3.6	450
Epoxy glass	.015	125–187	.03–.05	M105–115	1.8	.0005	3.8×10^{15}	5.5(@100)	360 volts/mil
Epoxy mineral	.011	180–190	.06–.15	M110	1.85	.002	10^{14}–10^{16}	4.4	400
Melamine cellulose	.030–.080	120–140	.1–.6	M118–124	1.47–1.52	.006–.015	0.8–2.0×10^{12}	7.9–9.5	300–400
Melamine cloth	.1–.34	125–150	.3–.6	—	1.4–1.5	.003–.005	1–3×10^{11}	8.1–12.6	250–340
Melamine glass MMI 30	.14–.23	180–186	.09–.6	—	1.9–2	.001–.003	2×10^{11}	9.7–11.1	170–240
Phenolic asbestos MFA 30	—	190	.35	M112	1.95	.0005–.0015	—	—	85
Phenolic cloth CFI–10	.16–.64	—	.8–1	M95–107	1.36–1.40	.002–.005	5–8×10^{11}	6.1–21.2	250–400
Phenolic cloth CFI–20	.64	4	.9–1	E79	1.37–1.40	.002–.005	6×10^{10}	5.2–21	300
Phenolic flock/flour	.25–.3	80(15518)	.3–1	M95–116	1.34–1.38	.004–.008	2×10^{11}	6–10	300–375
Phenolic glass	.02–.05	10–60	.5–1	M90–99	1.70–1.90	.0009	1×10^{12}	5.6–7.2	350–400
Phenolic GP	.05–.5	26–102	.2–1	M95–117	1.34–1.46	.004–.008	2×10^{11}	5–10	300–425
Phenolic GPI–100	.026(1MC)	125	.03	—	1.69	.0001–.001	—	5.4(1MC)	382
Phenolic nylon	.02	80	.20	M108	1.22	.012–.016	1×10^{12}	4	450
Phenolic rubber/flour	.14	8–10	1.4–2	M50	1.29–1.32	.007–.010	3.4×10^{9}	9	300
Urea cellulose	.035–.040	80–130	.5–.7	M116–120	1.47–1.52	.006–.14	$.5$–5×10^{11}	7–9.5	300–400
Silicone	.003–.02	175–240	.10–.30	M87	1.88	.0005	3×10^{14}	4.35	250–280
Silicone mineral	.002–.01	220–240+	.05–.22	M75–90	1.85–2.82	.005–.009	1×10^{4}	3.6–4.5	280–400

Table 1.5 General properties of reinforced thermoplastic

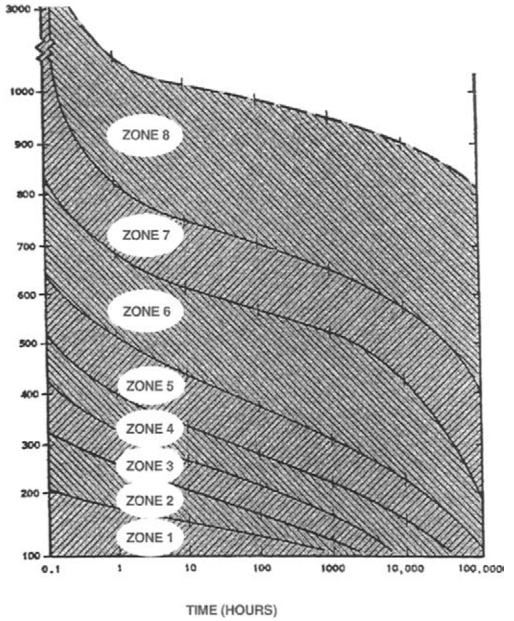
Resin material	Impact strength, notched izod ft lb/in., ⅛ in. bar	Tensile strength psi × 10^3	Tensile modulus psi × 10^3	Elongation, %	Flexural strength psi × 10^3	Compressive strength psi × 10^3	Compressive modulus psi × 10^3
Acetal glass filled	2–3	10.5–12.5	600–1000	2–3	15–16	10.5–13	—
Acrylonitrile butadiene stryrene glass filled	2.0–2.4	15–18	800–1030	2.5–3	23–27	15–18	3.75–490
Nylon 6 glass filled	3–4.3	21–30	—	1–3	27–37	19–22	—
Nylon 6/6 glass filled	2.5–3.7	20–30	—	1–3	28–37	18–24	—
Polycarbonate glass filled	3–4	18.5–20	1200–1700	1.4–2.2	25–27	18–19	—
Polyethylene glass filled	4.5	11	—	3.5	12	6	—
Polypropylene glass filled	3.5–7	8–9	450–900	2–3	10–11	6–7	—
Polystyrene glass filled	1.4–4.0	11–14.3	990–1290	1.1–1.3	15–20	14.5–17	—
Polyurethane glass filled	6–7	7–9	70	3–4	5.5–8.4	3.9	—
Styrene acrylonitrile glass filled	2.5–3	18	—	1–3	23–26	22	—

Resin material	Heat distortion, temp. °F, 264 psi	Coefficient thermal expansion, in./in.-°C×10^{-5}	Thermal conductivity, cal/cm^2-sec-°C/cm×10^{-4}	Volume resistivity, ohm-cm	Dielectric constant 60 cycles	Dielectric strength, ST ⅛" thickness, volts/mil	Arc resistance sec
Acetal glass filled	325–335	3.4–6.3	—	4×10^{16}	—	—	—
Acrylonitrile butadiene stryrene glass filled	230–240	2.9–3.6	—	10^{14}–10^{15}	—	—	—
Nylon 6 glass filled	420–423	1.4–2.3	5.9	1.5–3.0×10^{14}–10^{15}	4.5	400–580	92
Nylon 6/6 glass filled	498–502	1.6–3.1	5.2	2.6–5.5×10^{15}	4.0–4.5	480–500	100–148
Polycarbonate glass filled	295–300	1.6–2.0	1.29–1.80	1.5×10^{15}	3.7–3.8	475–482	7
Polyethylene glass filled	260	3	—	2.9×10^{16}	—	—	—
Polypropylene glass filled	280–300	2.9–4.3	—	1.7×10^{16}	2.26–2.54	317–475	73–77
Polystyrene glass filled	195–220	3.9–4.5	0.4	3.2–3.7×10^{16}	2.8–3.5	350–450	23–75
Polyurethane glass filled	180–200	—	—	—	—	—	—
Styrene acrylonitrile glass filled	225–230	2.7–3.3	—	4.4×10^{16}	3.5	510	16–65

Resin material	Water absorption 24 hr (%)	Rockwell hardness	Specific gravity	Mold shrinkage, in./in.	Clarity
Acetal glass filled	0.45–1.1	M75–90	1.55–1.7	0.002	Opaque
Acrylonitrile butadiene stryrene glass filled	.18–.21	M75–100	1.23–1.36	.001–.003	Opaque
Nylon 6 glass filled	0.9–1.1	E55–70	1.37–1.52	.003–.006	Translucent
Nylon 6/6 glass filled	.06–0.7	E60–80	1.37–1.52	.004–.007	Translucent
Polycarbonate glass filled	.08–.11	E55–90	1.35–1.52	.0025–.0010	Translucent
Polyethylene glass filled	0.04	R60	1.30	—	Translucent
Polypropylene glass filled	0.01–.05	R–90–105	1.06–1.24	.003–.008	Translucent
Polystyrene glass filled	.05–.07	E35–55	1.2–1.3	.0005–.004	Translucent
Polyurethane glass filled	0.2–0.3	R70–85	1.4–1.65	—	Opaque
Styrene acrylonitrile glass filled	.08–.15	E60–70	1.36–1.46	.0005–.0025	Translucent

Table 1.6 General properties of reinforced thermoset plastic

Resin	Properties	Uses	Limitations
Diallyl phthalate polymers	Good electricals, dimensional stability, chemical and heat resistance	Prepregs, ducting, radomes, aircraft, and missiles	
Epoxies	Good electricals, chemical resistance, high strength	Printed circuit board tooling, filament winding	Require heat curing for maximum performance.
Melamines	Good electricals, chemical and heat resistance	Decorative, electrical (arc and track resistance), circuit breakers	
Phenolics	Low cost, chemical resistance, good electricals, heat resistance; nonflammable; can be used to 350–400°F	Work horse—diverse mechanical and electrical applications	Dissolve in caustic unless specially treated
Polyesters	Good all-around properties, ease of fabrication, low cost, versatile	Corrugated sheeting, seating, boats, automotive, tanks and piping, aircraft, tote boxes	Not for strong oxidizers, aromatic solvents, concentrated caustic
Silicones	Heat resistance, good electricals	Electrical, aerospace	



EXAMPLES

ZONE 1	acrylic, cellulose esters, crystallizable block copolymers, LDPE, PS, vinyl polymers, SAN, SBR, urea-formaldehyde.
ZONE 2	acetal, ABS, chlorinated polyether, ethyl cellulose, ethylene-vinyl acetate copolymer, furan, ionomer, phenoxy, polyamides, PC, RDPE, PET, PP, PVC, urethane.
ZONE 3	polychlorotrifluoroethylene, vinylidene fluoride.
ZONE 4	alkyd, fluorinated ethylene-propylene, melamine-formaldehyde, phenol-furfural, polysulfone.
ZONE 5	acrylic, diallyl phthalate, epoxy, phenol-formaldehyde, TP polyester, polytetrafluoroethylene.
ZONE 6	parylene, polybenzimidazole, polyphenylene, silicone.
ZONE 7	polyamide-imide, polyimide;
ZONE 8	plastics now being developed using rigid linear macromolecules rather than crystallization and cross-linking.

Figure 1.5 Temperature-time guides retaining 50%. plastic properties (courtesy of Plastics FALLO)

significantly affected by residence time. However, some TPs can significantly lose certain properties. If incorrect methods were used in granulating recycled material, more degradation will occur.

Plastic Memory

TPs can be bent, pulled, or squeezed into various useful shapes, but eventually, especially if you add heat, they return to their original form. During this shaping with other materials they alter their molecular structure orientation to accommodate the deformation permanently. Not so with plastics. Plastics temporarily assume the deformed shape but always maintain internal stresses that want to force the material back to its original shape. This behavior is known as plastic memory. It can be an unwanted behavior. But when property applied plastic memory offers some interesting behavior possibilities for products. The time/temperature-dependent change in mechanical properties results from stress relaxation and other viscoelastic phenomena typical of plastics. When the change is an unwanted limitation it is called creep. When the change is skillfully adapted to the overall design, it is called plastic memory.

Most plastic products can be produced with a built-in memory. That is, the tendency to move into a new shape is included as an integral part of the design. So then, after the products are assembled in place, a small amount of heat can coax them to change shape. TP products can be deformed during assembly then allowed returning to their original shape. In this case products can be stretched around obstacles or made to conform to unavoidable irregularities without permanent damage.

Potential memory exists in all TPs. Polyolefins, neoprene, silicone, and other crosslinkable polymers can be given a memory either by radiation or by chemically curing. Fluorocarbons, however, need no curing. And when the phenomenon is applied to fluorocarbons such as TFE, FEP, ETFE, ECTFE, CTFE, and PVF interesting high temperature or wear resistant applications are possible.

Thermal Conductivity

TC is the rate at which a material will conduct heat energy along its length or through its thickness. ASTM tests give an indication of how much heat must be added to a unit mass of plastic in order to raise its temperature 1C. This is an important factor, since there are plastics that are often used as effective heat insulation in heat-generating applications and in structures where heat dissipation is important. The high degree of the molecular order for crystalline TPs makes their values tend to be twice those of the amorphous types.

In general, TC is low for plastics and the plastic's structure does not alter its value significantly. TC of plastics depends on several variables and cannot be reported as a single factor. But it is possible to ascertain the two principal dependencies of temperature and molecular orientation (MO). In fact, MO may vary within a product producing a variation in thermal conductivity. To increase TC the usual approach is to add metallic fillers, glass fibers, or electrically insulating fillers such as alumina. Foaming can be used to decrease thermal conductivity.

Several factors make thermally conductive TPs attractive for different market segments. In the electronics market, the trend is toward smaller, lighter, and faster. As fabrication becomes faster, the amount of heat generated by the chip increases; a typical 486 chip generates about 5 watts of power while the newer Pentium 11 chips can generate more than 30 watts. The inability to remove the heat generated by these chips greatly reduces their operating life. The design flexibility afforded by thermally conductive TPs provides solutions to increased demands on chip cooling systems.

In the lighting market they are useful. Here, improving TP thermal capabilities with product integration and lower fabricating costs can improve the operating life span of fluorescent fixtures. Thus, improvements in thermal performance could drive the replacement of traditional metals in these applications.

In the past engineering TPs have replaced metal in numerous products in many industries by providing improvements in thermal properties.[146] The ability to prepare and compound material properties through the choice of plastics with additives, fillers and reinforcements, has allowed the development of the flexibility inherent in TPs to meet the performance requirements required in these different applications.

Specific Heat

The specific heat or heat capacity of a unit mass of material is the amount of energy required to raise its temperature 1C. It can be measured either at constant pressure or constant volume. At constant pressure it can be larger than at constant volume, because additional energy is required to bring about a volume change against external pressure. The specific heat of amorphous plastics increases with temperature in an approximately linear fashion below and above T_g, but a steplike change occurs near the T_g. No such stepping occurs with crystalline types. For plastics, specific heat is usually reported during constant pressure heating. Plastics differ from traditional engineering materials because their specific heat is temperature sensitive.

Thermal Diffusivity

Whereas specific heat is a measure of energy, thermal diffusivity is a measure of the rate at which energy is transmitted through a given plastic. It relates directly to processability. In contrast, metals have values hundreds of times larger than those of plastics. Thermal diffusivity determines plastics' rate of change with time. Although this function depends on thermal conductivity, specific heat at constant pressure, and density, all of which vary with temperature, thermal diffusivity is relatively constant.

Coefficient of Linear Thermal Expansion

Like metals, plastics generally expand when heated and contract when cooled. Usually temperature change with TPs are greater than metals. The coefficient of linear thermal expansion (CLTE) is the ratio between the change of a linear dimension to the original dimension of the material per unit change in temperature (per ASTM standards). It is generally given as cm/cm/C or in./in./F.

If a plastic product is free to expand and contract, its thermal expansion property will usually have little significance. The CLTE is an important consideration if dissimilar materials like one plastic to another or a plastic to metal and so forth are to be assembled where material expansion or contraction is restricted. The type of plastic and RP, particularly the glass fibers content and its orientation influences the CLTE. It is especially important if the temperature range includes a thermal transition such as T_g. Products have to take into account the dimensional changes that can occur during fabrication and during its useful service life. With a mismatched CLTE there could be destruction of plastics from factors such as cracking or buckling. A temperature change results in developing thermal stresses in the product. The magnitude of these stresses will depend on the temperature change, the method of attachment and relative expansion, and the modulus characteristics of the two materials at the point of the exposed heat. Normally, all this activity with dimensional changes is available from material suppliers readily enough to let one apply a logical approach and understand what could happen.

There are different approaches to eliminate or significantly reduce all sources of thermal stress. Examples include select a material with the same or a similar CLTE. If a plastic is to be attached to a more-rigid material, use mechanical fasteners with slotted or oversized holes to permit expansion and contraction to occur or do not fasten dissimilar materials tightly. Use adhesives that remain ductile, such as urethane and silicone, through the product's expected end-use temperature. Expansion and contraction can be controlled in plastic by adding fillers or reinforcements. With certain additives the CLTE value could be zero or near zero. For example, plastic with a graphite filler contracts rather than expands during a temperature rise. RPs with only glass fiber reinforcement can be used to match those of metal and other materials. In fact, TSs can be specifically compounded to have little or no change.

In addition to dimensional changes from changes in temperature, other types of dimensional instability are possible in plastics as in other materials. Water-absorbing plastics, such as certain nylons, may expand and shrink as they gain or lose water, or even as the relative humidity changes. The migration or leaching of plasticizers, as in certain PVCs, can result in slight dimensional change.

Temperature Index

The Underwriters Laboratories (UL) tests are recognized by various industries to provide continuous temperature ratings, particularly in electrical applications. These ratings include separate listings for electrical properties, mechanical properties including impact, and mechanical properties without impact. The temperature index is important if the final plastic product has to receive UL recognition or approval.

Corrosion Resistance

Complex corrosive environments results in at least 30wt% of total yearly plastics production being required in buildings, chemical plants, transportation, packaging, and communications. Plastics find many ways to save some of the billion dollars lost each year by industry due to the many forms of corrosion.

Corrosion is fundamentally a problem associated with metals. Since plastics are electrically insulating they are not subject to this type of damage. Plastics are basically noncorrosive. However, there are those that can be affected when exposed to corrosive environments. It is material deterioration or destruction of materials and properties brought about through electrochemical, chemical, and mechanical actions.

Corrosion resistance is the ability of a material to withstand contact with ambient natural factors or those of a particular artificially created atmosphere without degradation or change in properties. Since plastics (not containing metallic additives) are not subjected to electrolytic corrosion, they are widely used where this property is required alone as a product or as coatings and linings for material subjected to corrosion such as in chemical and water filtration plants, mold/die, etc. Plastics are used as protective coatings on products such as steel rod, concrete steel reinforcement, mold cavity coating, plasticator screw coating, etc.

Chemical Resistance

Part of the wide acceptance of plastics is from their relative compatibility to chemicals, particularly to moisture, as compared to that of other materials. Because plastics are largely immune to the electrochemical corrosion to which metals are susceptible, they can frequently be used profitably to contain water and corrosive chemicals that would attack metals.

Plastics are often used in corrosive environments for chemical tanks, water treatment plants, and piping to handle drainage, sewage, and water supply. Structural shapes for use under corrosive conditions often take advantage of the properties of RPs. Today's underground tanks must last thirty or more years without undue maintenance. To meet these criteria they must be able to maintain their structural integrity and resist the corrosive effects of soil and gasoline including gasoline that has been contaminated with moisture and soil. Structural shapes for use under corrosive conditions often take advantage of the properties of RPs.[1, 4, 173]

Fire Property

Like other materials, hot enough fires can destroy all plastics. Some burn readily, others slowly, others only with difficulty; still others do not support combustion after the removal of the flame. There are certain plastics used to withstand the reentry temperature of 2,500F (1,370C) that occurs when a spacecraft returns into the earth's atmosphere; the time exposure is parts of a millisecond. Different industry standards and tests can be used to rate plastics at these various degrees of combustibility.

Steel and Plastic

Plastics' behavior in fire depends upon the nature and scale of the fire as well as the surrounding conditions and how the products are designed. For example, the virtually all-plastic 35 mm slide projectors use a very hot electric bulb. When designed with a metal light and heat reflector with an air-circulating fan, the all-plastic projector operates with no fire hazard.

Steel structural beams cannot take the heat of a fire operating at and above 830C (1500F); they just loose all their strength, modulus of elasticity, etc. To protect steel from this environment they can obtain a temporary short time protection by being covered with products such as concrete and certain plastics. To significantly extend the life of structural beams hardwood (thicker, etc.) can be used; thus people can escape even though the wood slowly burns. The more useful and reliable structural beams would be using reinforced plastics (RPs) that meet structural performance requirements with even a more extended supporting life than wood. To date these RPs are not used in this type of fire environment primarily because their cost are very high.

Permeability

Depending on what is required the different plastics can provide different rates of permeability properties.

There are materials with low or no permeability to different environments or products. Different factors influence performance such as being pinhole-free; chemical composition, crosslinking, modification, molecular orientation; density, and thickness. The coinjection and coextrusion molding processes that combine different plastics, including those with specific permeability capabilities, are examples of methods used to reduce permeability while retaining other desirable properties (Chapters 2 and 6).

Radiation

In general, plastics are superior to elastomers in radiation resistance but are inferior to metals and ceramics. The materials that will respond satisfactorily in the range of 10^{10} and 10^{11} erg per gram are glass and asbestos-filled phenolics, certain epoxies, polyurethane, polystyrene, mineral-filled polyesters, silicone, and furane. The next group of plastics in order of radiation resistance includes polyethylene, melamine, urea formaldehyde, unfilled phenolic, and silicone resins. Those materials that have poor radiation resistance include methyl methacrylate, unfilled polyesters, cellulosics, polyamides, and fluorocarbons.

Craze/Crack

Many TPs will craze or crack under certain environmental conditions, and products that are highly stressed mechanically must be checked very carefully. Polypropylene, ionomer, chlorinated polyether, phenoxy, EVA, and linear polyethylene offer greater freedom from stress crazing than some other TPs. Solvents may crack products held under stress. TSs is generally preferable for products under continuous loads.

Drying plastic

Plastic materials absorb moisture that may be insignificant or damaging. All plastics, to some degree, are influenced by the amount of moisture or water they contain before processing. Moisture may reduce processing and product performances. With minimal amounts in many plastics, mechanical, physical, electrical, aesthetic, and other properties may be affected or may be of no consequence. For the record let it be known that in the past probably 80% of fabricating problems was due to inadequate drying of all types of plastics. Now it could be down to 40%.

There are hygroscopic (such as PET, PC, nylon, PMMA, PUR, & ABS) and nonhygroscopic plastics. The hygroscopic types absorb moisture, which then has to be carefully removed before the plastics can be processed into acceptable products. Low concentrations, as specified by the plastic supplier, can be achieved through efficient drying systems and properly handling the dried plastic prior to and during molding, extrusion, etc. When desired processor can have these hygroscopic plastics properly dried and shipped in sealed containers.

Tray dryers or mechanical convection hot-air dryers that are adequate for nonhygroscopic plastics are not capable of removing water to the degree necessary for the proper processing of hygroscopic types or their compounds, particularly during periods of high humidity (Table 1.7).

Table 1.7 Examples of drying different plastics (courtesy of Spirex Corp.)

MATERIAL	DRYING TEMP (°F)	DRYING TIME (HRS.)
ABS	180	3-4
Acetal	210	2
Acrylic	160-180	2
Barex	160	6
Cellulosics	160	6
Ionomer	150	8
Nylon	160	6
PC	250	3-4
PE w/40% black	195	3
PET	325-375	4-6
PBT	250	2-3
PETG	160	3-4
Polyamide	250	2
Polyester Elastomer	225	3
PEM	300	4
PES	300	4
PPS	300	6
PP	195	1
PS (GP)	180	1
HIPS	180	1.5
Polysulfone	250	4
PU	180	3
PPO	255	2
Rynite	250	2
SAN	180	2
Styrene	180	2
Vinyls (PVC)	160	1

The drying operation for non-hygroscopic plastics is different. They collect moisture only on the surface. Drying this surface moisture can be accomplished by simply passing warm air over the material. Moisture leaves the plastic in favor of the warm air resulting in drying the non-hygroscopic plastics.

There are certain plastics that, when compounded with certain additives such as color, could have devastating results. Day-to-night temperature changes is an example of how moisture contamination can be a source of problems if not adequately eliminated when plastic materials are exposed to the air; otherwise it has an accumulative effect. The critical moisture content (average material moisture content at the end of the constant-rate-drying period) is a function of material properties, the constant-rate of drying, and particle size.

Although it is sometimes possible to select a suitable drying method simply by evaluating variables such as humidities and temperatures when removing unbound moisture, many plastic drying processes involve removal of bound moisture retained in capillaries among fine particles or moisture actually dissolved in the plastic. Knowledge of internal liquid and vapor mass-transfer mechanisms applies. Measuring drying-rate behavior under control conditions best identifies these mechanisms. A change in material handling method or any operating variable, such as heating rate, may effect mass transfer.

During the drying process at ambient temperature and 50% relative humidity, the vapor pressure of water outside a plastic is greater than within. Moisture migrates into the plastic, increasing its moisture content until a state of equilibrium exists inside and outside the plastic. But conditions are very different inside a drying hopper (etc.) with controlled environment. At a temperature of 350F (170C) and –40F (–40C) dew point, the vapor pressure of the water inside the plastic is much greater than the vapor pressure of the water in the surrounding area. Result is moisture migrates out of the plastic and into the surrounding air stream, where it is carried away to the desiccant bed of the dryer.

Before drying can begin, a wet material must be heated to such a temperature that the vapor pressure of the liquid content exceeds the partial pressure of the corresponding vapor in the surrounding atmosphere. Different devices such as a psychometric chart can conveniently study the effect of the atmospheric vapor content on the rate of the dryer as well as the effect of the material temperature. It plots moisture content dry-bulb, wet-bulb, or saturation temperature, and enthalpy at saturation.

First one determines from the material supplier and/or experience, the plastic's moisture content limit. Next determine which procedure will be used in determining water content, such as weighing, drying, and/or re-weighing. These procedures have definite limitations. Fast automatic analyzers, suitable for use with a wide variety of plastic systems, are available that provide quick and accurate data for obtaining the in-plant moisture control of plastics.

Drying or keeping moisture content at designated low levels is important, particularly for hygroscopic types where moisture is on the surface and particularly collected internal. They have to be carefully dried prior to processing. Usually the moisture content is >0.02 wt%. In practice, a drying heat 30C below the softening heat has proved successful in preventing caking of the plastic in a dryer. Drying time varies in the range of 2 to 4 h, depending on moisture content. As a rule of thumb, the drying air should have a dew point of –30F (–34C) and the capability of being heated up to 250F (121C). It takes about $1\text{–ft}^3\ \text{min}^{-1}$ of plastic processed when using a desiccant dryer. The pressure drop through the bed should be less than 1 mm H_2O per mm of bed height. Simple tray dryers or mechanical convection, hot-air dryers, while adequate for certain plastics, are incapable of removing enough water for the proper processing of hygroscopic plastics, particularly during periods of high humidity.

Hygroscopic plastics are commonly passed through dehumidifying hopper dryers before entering a screw plasticator. However, except where extremely expensive protective measures are taken, the drying may be inadequate, or the moisture regained may be too rapid to avoid product defects unless barrel venting is provided (Chapter 3). To ensure proper drying for delicate parts such as lenses and compact disks, the combination of drying the plastics and using vented barrels provides a double check. However, just using vented extruders can be suitable.

Plastic usage for a given process should be measured so as to determine how much plastic should be loaded into the hopper. Usually the hopper should hold enough dried plastic for ½ to 1 hour's production. This action is taken so as to prevent storage in the hopper for any length of time eliminating potential moisture contamination from the surrounding atmospheric area. Care should be taken to ensure that hygroscopic plastics are in an unheated hopper for no more than ½ to 1 hr, or as specified by the material supplier (and/or experience).

Variable

There is continuous progress in regard to reducing the existing plastic material and equipment variabilities (as there are for steel and other materials). Target is always to improve their manufacturing and process control capabilities. However they still exist. To ensure minimizing material and process variables different tests and setting limits are important. Even set within limits, processing the materials could result in inferior products. As an example the material specification from a supplier will provide an available minimum to maximum value such as molecular weight distribution (MWD). It is determined that when material arrives all on the maximum side it produces acceptable products. However when all the material arrives on the minimum side process control has to be changed in order to produce acceptable products (Chapter 3).

In order to judge performance capabilities that exist within the controlled variabilities, there must be a reference to measure performance against. As an example, the injection mold cavity pressure profile is a parameter that is easily influenced by variations in the materials. Injection molding related to this parameter are four groups of controls that when put together influences the processing profile:

1 melt viscosity and fill rate,
2 boost time,
3 pack and hold pressures, and
4 recovery of plasticator.

Thus material variations may be directly related to the cavity pressure variation (Chapter 4).

Even though equipment operations have understandable but controllable variables that influence processing, the usual most uncontrollable variable in the process can be the plastic material. A specific plastic will have a range of performances. However, more significant, is the degree of properly compounding or blending by the plastic manufacturer, converter, or in-house by the fabricator is important. Most additives, fillers, and/or reinforcements when not properly compounded will significantly influence processability and molded product performances.

A very important factor that should not be overlooked by a designer, processor, analyst, statistician, etc. is that most conventional and commercial tabulated material data and plots, such as tensile strength, are average or mean values. They would imply a 50% survival rate when the material value below the mean processes unacceptable products. Target is to obtain some level of reliability that will account for material variations and other variations that can occur during the product design to processing the plastics

In addition to material variables, there are a number of factors in equipment hardware and controls that cause processing variabilities. They include factors such as accuracy of machining component equipment parts, method and degree of accuracy during the assembly of component parts, temperature/pressure control capability particularly when interrelated with time and heat transfer uniformity in metal components such as those used in molds and dies.

These variables are controllable within limits to produce useful and cost efficient products. What is important to appreciate is that during the past many decades' improvements in equipment have made exceptional strides in significantly reducing operating variabilities or limitations. This action will continue into the future since there is a rather endless improvement in performance of steels and other materials and methods of controlling such as fuzzy control (Chapter 3). Growth is occurring in applying fuzzy logic that in 1981 was based on the idea to mimic the control actions of the human operator. Unfortunately these variables and problems exist in all industries.[1]

Advantage and limitation

As a construction material, plastics provide practically unlimited benefits to the fabrication of products, but unfortunately, as with other materials, no one specific plastic exhibits all these positive characteristics. The successful application of their strengths and an understanding of their weaknesses (limitations) will allow to produce useful products. With any material (plastic, steel, etc.) products fail not because of its disadvantage(s). They failed because someone did not perform their selection in the proper manner and/or incorrectly processed the plastic.

There is a wide variation in properties among the over 35,000 commercially available materials classified as plastics. They now represent an important, highly versatile group of commodity and engineering plastics. Like steel, wood, and other materials, specific groups of plastics can be characterized as having certain properties (Chapter 2). As with other materials, for every advantage cited for a certain material, a corresponding disadvantage can probably be found in another.

Many plastics that are extensively used worldwide are typically not as strong or as stiff as metals and they are prone to dimensional changes especially under load or heat. They are used in stead of metals (in millions of products) because their performance meet requirements. However there are plastics that meet dimensional tight requirements,

1 INTRODUCTION

Overview

The growth of the plastic industry for over a century has been spectacular evolving into today's routine to sophisticated high performance products. Examples of these products include packaging, building and construction, electrical and electronic, appliance, automotive, aircraft, and practically all markets worldwide. The plastic industry is the fourth largest industry in USA providing 1.5 million jobs. Because of the wide range of products meeting different performance/cost requirements and the large number of materials (35,000) used with different processes, material and process selection can become quite complex if not properly approached as reviewed in this book.

Plastic selection ultimately depends upon the performance criteria of the product that usually includes aesthetics and cost effectiveness. Analyzing how a material is expected to perform with respect to requirements such as mechanical space, electrical, and chemical requirements combined with time and temperature can be essential to the selection process. The design engineer translates product requirements into material properties. Characteristics and properties of materials that correlate with known performances are referred to as engineering properties. They include such properties as tensile strength and modulus of elasticity, impact, hardness, chemical resistance, flammability, stress crack resistance, and temperature tolerance. Other important considerations encompass such factors as optical clarity, gloss, UV stability, and weatherability.[1, 248, 482]

It would be difficult to imagine the modern world without plastics. Today they are an integral part of everyone's life-style, with products varying from commonplace domestic to sophisticated scientific products.[451] As a matter of fact, many of the technical wonders we take

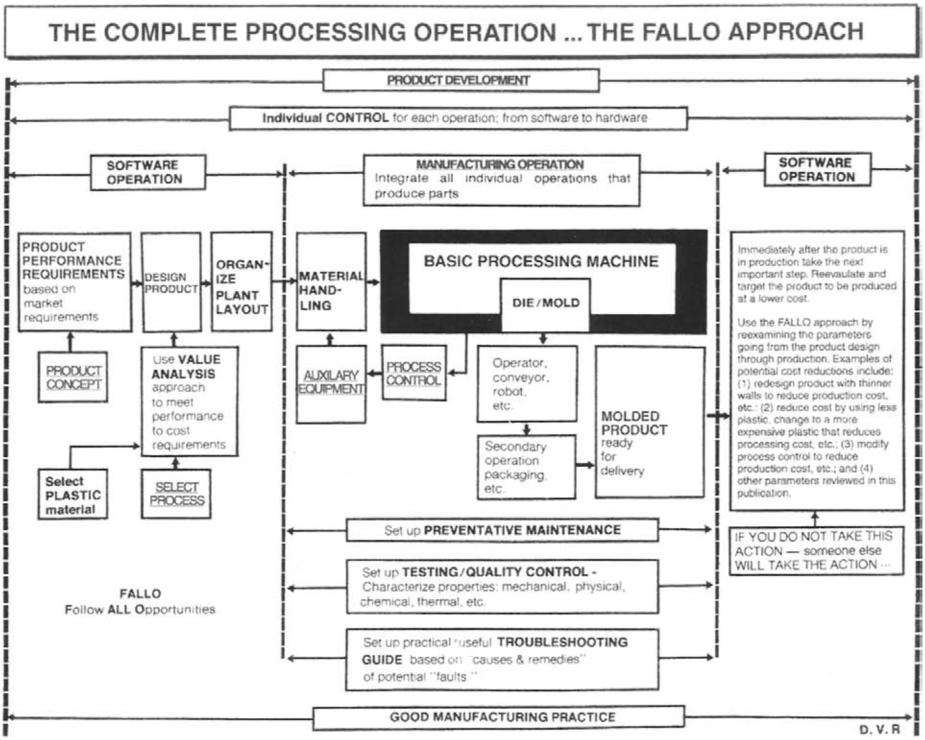

THE COMPLETE PROCESSING OPERATION ... THE FALLO APPROACH
PRODUCT DEVELOPMENT
Individual CONTROL for each operation; from software to hardware
SOFTWARE OPERATION
MANUFACTURING OPERATION
Integrate all individual operations that produce parts
SOFTWARE OPERATION
PRODUCT PERFORMANCE REQUIREMENTS based on market requirements
DESIGN PRODUCT
ORGANIZE PLANT LAYOUT
MATERIAL HANDLING
BASIC PROCESSING MACHINE
DIE/MOLD
PRODUCT CONCEPT
Use VALUE ANALYSIS approach to meet performance to cost requirements
AUXILARY EQUIPMENT
PROCESS CONTROL
Operator, conveyor, robot, etc.
MOLDED PRODUCT ready for delivery
Secondary operation packaging, etc.
Select PLASTIC material
SELECT PROCESS
Immediately after the product is in production take the next important step. Reevaulate and target the product to be produced at a lower cost.
Use the FALLO approach by reexamining the parameters going from the product design through production. Examples of potential cost reductions include: (1) redesign product with thinner walls to reduce production cost, etc.; (2) reduce cost by using less plastic, change to a more expensive plastic that reduces processing cost, etc.; (3) modify process control to reduce production cost, etc.; and (4) other parameters reviewed in this publication.
Set up PREVENTATIVE MAINTENANCE
IF YOU DO NOT TAKE THIS ACTION — someone else WILL TAKE THE ACTION ...
Set up TESTING/QUALITY CONTROL - Characterize properties: mechanical, physical, chemical, thermal, etc.
FALLO
Follow ALL Opportunities
Set up practical/useful TROUBLESHOOTING GUIDE based on "causes & remedies" of potential "faults"
GOOD MANUFACTURING PRACTICE
D. V. R

Figure 1.6 FALLO approach includes going from material to fabricated product (courtesy of Plastics FALLO)

successful, all of which must be coordinated and interrelated. It starts with the design that involves specifying the plastic and specifying the manufacturing process. The specific process (injection, extrusion, blow molding, thermoforming, and so forth) is an important part of the overall scheme and should not be problematic. Basically the FALLO approach diagram consists of:

1. Designing a product to meet performance and manufacturing requirements at the lowest cost;[482]
2. Specifying the proper plastic material that meet product performance requirements after being processed;
3. Specifying the complete equipment line by:
    (a) designing the tool (die, mold) "around" the product,
    (b) putting the "proper performing" fabricating process "around" the tool,
    (c) setting up auxiliary equipment (up-stream to down-stream) to "match" the operation of the complete line,

    (d) setting up the required "complete controls" (such as testing, quality control, troubleshooting, maintenance, data recording, etc.) to target in meeting "zero defects";

4 Purchasing and properly warehousing plastic materials and maintaining equipment.

Using this type of approach leads to maximizing product's profitability. If processing is to be contracted ensure that the proper equipment is available and used. This interrelationship is different from that of most other materials, where the designer is usually limited to using specific prefabricated forms that are bonded, welded, bent, and so on.

Summary of Figure 1.6 is that acceptable products will be produced. It highlights the flow pattern to be successful and profitable. Recognize that first to market with a new product captures 80% of market share.

2 PLASTIC PROPERTY

Overview

The plastic property information and data presented in Tables 1.2 to 1.6 and Table 2.1 provide comparative guides to thermoplastics (TPs) and thermosets (TSs). There is an endless amount of data available for many available and new plastic materials.[79] Unfortunately, as with other materials, there does not exist only one plastic material that will meet all performance requirements. However, it can be stated that for practically any product requirements, particularly when not including cost for very few products, more so than with other materials, there is a plastic that can be used. Plastics provide more property variations than any other material.[16, 25, 75–78, 248, 486]

Readers can obtain the latest and more detailed data and information from suppliers and/or software programs. The guides presented in this book only provide a means to compare the general performances of different plastics. Since new developments in plastic materials are always on the horizon it is important to keep up to date. It is important to ensure that the fabricating process to be used to produce a product provides the properties desired (Chapter 3). Much of the market success or failure of a plastic product can be attributed to the initial choices of material, process, and their cost.

Plastics are families of materials each with their own special advantages. An example is polyethylene (PE) with its many types include low density PE (LDPE), high density PE (HDPE), High molecular weight PE (HMWPE), etc. The major consideration for a designer and/or fabricator is to analyze what is required as regards to product performances and develop a logical selection procedure from what is available.

Table 2.1 General properties of plastics

	Specific gravity	Flame color (copper wire)		Color	Smoke density	Odor	Solvents
		As is	Melts/soft				
Polypropylene	0.85–0.9	Blue yellow	Yes (trans.)	White	Very little	Heavy	Toluene (slowly slight)
LDPE	0.91–0.93	Blue yellow	Yes (trans.)	White	Very little	Candle wax	Dipropylene glycol
HDPE	0.93–0.96	Blue yellow	Yes (trans.)	White	Very little	Candle wax	Toluene
Epoxy	1–1.25	Orange yellow (green)	No	Black		Phenolic	
Chlorinated PE	1–24	Green	Yes				Toluene[b]
Polystyrene	1.05–1.08	Orange yellow	Yes	Black	Dense	Sweet marigolds	Diethyl benzene
Polyvinyl butyral	1.07–1.08	Blue mantle yellow	Yes (trans.)			Rancid butter	
Nylon	1.09–1.14	Blue mantle yellow	Yes			Burnt hair	
Ethyl cellulose	1.1–1.16	Blue white	Yes			Sweet	See-amyl alcohol
Polyester	1.12–1.46	Yellow	No	Black	Dense	Sweet (resinous)	
Vinyl chloride	1.15–1.65	(Green) yellow orange	Yes, softening	White to green	Little	Acrid chlorine	Toluene
Acrylic	1.18–1.19	Blue mantle yellow orange	Yes (trans.)	Some black		Floral burnt fat	Toluene
Vinyl acetate	1.19	Dark yellow	Yes	Black		Acetic	Sec-hexyl alcohol cyclohexanol acetionitrile
Polycarbonate	1.20	Orange yellow	No	Black		Phenolic sweet	Toluene
Cellulose acetate	1.27–1.34	Dark yellow, mauve blue	Yes	Black		Acetic vinegar	Furfuryl alcohol and acetionitrile
Casein	1.35	Yellow	No	Gray		Burnt milk	
Cellulose nitrate	1.35–1.40	Intense white	Yes			No odor	Dipropylene glycol and acetionitrile
Acetal	1.41–1.42	Blue mantle yellow	Yes			Formaldehyde	
Urea formaldehyde	1.47–1.52		No			Urinous	
Melamine formaldehyde	1.50–2.20		No			Fish	
Phenol formaldehyde	1.55–1.90		No			Phenolic	

Recognize that most of the plastic products produced only have to meet the usual requirements we humans have to endure such as the environment (temperature, pressure, etc.). The ranges of properties in different plastics encompass all types of environmental and load conditions, each with its own individual, yet broad, range of properties. These properties can take into consideration wear resistance, integral color, impact resistance, transparency, energy absorption, ductility, thermal and sound insulation, weight, and so forth. Thus there is no need for someone to identify that most plastics can not take heat like steels. Also recognize that most plastics in use also do not have a high modulus of elasticity or long creep and fatigue behaviors because they are not required in their respective product designs. However there are plastics with extremely high heat resistance and high modulus with very long creep and fatigue behaviors. These type products have performed in service for long periods of time with some performing well over a half-century. For certain plastic products there are definite properties (modulus of elasticity, temperature, chemical resistance, load, etc.) that have far better performance than steels and other materials.[1, 2, 451, 465]

Highly favorable conditions such as less density, strength through shape, good thermal insulation, a high degree of mechanical dampening, high resistance to corrosion and chemical attack, and exceptional electric resistance exist for certain plastics. There are also those that will deteriorate when exposed to sunlight, weather, or ultraviolet light, but then there are those that resist such deterioration.

Different plastics can be combined producing a product meeting different properties. When compounding or alloying certain plastics synergistic effects can occur. As reviewed in Chapter 1, practically all plastics include different additives, fillers, and/or reinforcements providing all kinds of properties including those with synergistic effects. Different plastics can just be stacked together, but with available processes the more popular technique is to process them together so that each material retains its individuality yet has a bond with the adjoining plastics. These processes include coinjection, coextrusion, laminating, and coating (Chapters 4 to 10). Each of the individual plastics can provide such characteristics as wear resistance, water barrier, electrical conductor, and adding strength. Low cost and recycled plastics can be "sandwiched" between other expensive, high performance plastics so they only act as a filler, increase strength, etc.

To meet fabricated dimensional tolerances different approaches are used. They include use of specific fillers and reinforcements and process control (Chapter 3). Popular filler used is short glass fibers (Chapter 15). Over 50wt% of all types of glass fibers used with different plastics and by different processes are used in injection molding compounds. Table 2.2 shows the shrinkage of different unreinforced plastics ad glass fiber reinforced plastics based on ASTM testing procedures.

Different barrier plastics meet different requirements. A very popular barrier plastic is EVOH (ethylene-vinyl alcohol copolymer) that can be tailored to the needs of packages and other products.[80] Generally the thickness ranges from 0.5 to 3.0% of the wall thickness; it can be thicker if higher barrier is required. Generally EVOH thickness greater than 8% of the container sidewall can lead to internal structural failures that can fail on drop tests. Also a very thick layer tends to be difficult to process consistently. The EVOH's crack resistance improves as its ethylene content increases.

Use can be made of conventional type plastics that are available in sheet form, in I-beams, or other forms as is common with most other materials. Although this approach with plastics has its place, the real

Table 2.2 Example of plastic shrinkage without and with glass fiber

	Avg. rate per ASTM D 955	
	0.125 in. (3.18 mm)	0.250 in. (6.35 mm)
ABS		
Unreinforced	0.004	0.007
30% glass fiber	0.001	0.0015
Acetal, copolymer		
Unreinforced	0.017	0.021
30% glass fiber	0.003	NA
HDPE, homo		
Unreinforced	0.015	0.030
30% glass fiber	0.003	0.004
Nylon 6		
Unreinforced	0.013	0.016
30% glass fiber	0.0035	0.0045
Nylon 6/6		
Unreinforced	0.016	0.022
30% glass fiber	0.005	0.0055
PBT polyester		
Unreinforced	0.012	0.018
30% glass fiber	0.003	0.0045
Polycarbonate		
Unreinforced	0.005	0.007
30% glass fiber	0.001	0.002
Polyether sulfone		
Unreinforced	0.006	0.007
30% glass fiber	0.002	0.003
Polyether-etherketone		
Unreinforced	0.011	0.013
30% glass fiber	0.002	0.003
Polyetherimide		
Unreinforced	0.005	0.007
30% glass fiber	0.002	0.004
Polyphenylene oxide/PS alloy		
Unreinforced	0.005	0.008
30% glass fiber	0.001	0.002
Polyphenylene sulfide		
Unreinforced	0.011	0.004
30% glass fiber	0.002	NA
Polypropylene, homo		
Unreinforced	0.015	0.025
30% glass fiber	0.0035	0.004
Polystyrene		
Unreinforced	0.004	0.006
30% glass fiber	0.005	0.001

advantage with plastic lies in the ability to process them to fit the design shape, particularly when it comes to complex shapes. Examples include two or more products with mechanical and electrical connections, living hinges, colors, snap fits that can be combined into one product, and so on.[1]

Plastics can also be combined with other materials such as aluminum, steel, and wood to provide specific properties. Examples include extruded PVC/wood window frames and extruded plastic film/aluminum-foil packaging material. All combinations may require that certain aspects of compatibility such as processing temperature, bondability, and coefficient of expansion or contraction exist.

Plastic performance

The many different types of plastics to be reviewed in the following sections will highlight their mainbehaviors. Some of these plastics are reviewed in other chapters providing additional information since they provide special characteristics applicable to that chapter's subject. What is presented will provide familiarity with the variations of properties existing in plastics.

As an initial step, the product designer must know and/or anticipate the conditions of use and the performance requirements of the product such as life expectancy, size, condition of use, shape, color, strength, stiffness, and cost.[1, 482] A clear and accurate definition of product requirements will lead directly to choice of the material of construction.

As a general rule, it is considered desirable to examine the properties of three or more materials before making a final choice. Material suppliers should be asked to participate in type and grade selection so that their experience is part of the input. The technology of manufacturing plastic materials, as with other materials (steel, wood, etc.) results in that the same plastic compounds supplied from various sources will generally not deliver the same results in a product. As a matter of record, even each individual supplier furnishes their product under a batch number, so that any variation can be tied down to the exact condition of the raw-material production. Taking into account manufacturing tolerances of the plastics, plus variables of equipment and procedure (Chapter 1), it becomes apparent that checking several types of materials from the same and/or from different sources is an important part of material selection. In turn it usually requires setting up different process controls to meet the plastic variables.

Experience has proven that the so-called interchangeable grades of materials have to be evaluated carefully as to their affect on the quality of a product. Another important consideration as far as equivalent grade of material is concerned is its processing characteristics. There can be large differences in properties of a product and test data if the processability features vary from grade to grade. It must always be remembered that test data have been obtained from simple and easy to process shapes and do not necessarily reflect results in complex product configurations. This situation is similar to those encountered with other materials (steel, wood, glass, etc.).

Most plastics are used to produce products because they have desirable mechanical properties at an economical cost. For this reason their mechanical properties may be considered the most important of all the physical, chemical, electrical, and other considerations for most applications. Thus, everyone designing with such materials needs at least some elementary knowledge of their mechanical behavior and how they can be modified by the numerous structural geometric shape factors that can be in plastic.[1]

Thermoplastic

These plastics represent at least 90wt% of all plastics consumed worldwide. Unlike thermoset plastics, they are in many cases reprocessable without any or serious losses of properties. There are those than can have limitations of heat-distortion temperatures, cold flow and creep, and are more likely to be damaged by chemical solvent attack from paints, adhesives, and cleaners. When injection molded, dimensional integrity and ultimate strength are more dependent on the proper process control molding parameters than is generally the case with TSs.

Polyolefin

Within the family of polyolefins there are many individual families that include low density polyethylenes, linear low density polyethylenes, very low polyethylenes, ultra low polyethylenes, high molecular weight polyethylenes, ultra high molecular weight polyethylenes, polyethylene terephthalates, ethylene-vinyl acetate polyethylenes, chlorinated polyethylenes, crosslinked polyethylenes, polypropylenes, polybutylenes, polyisobutylene, ionomers, polymethylpentene, thermoplastic polyolefin elastomers (polyolefin elastomers, TP), and many others.

Some of these plastics often compete for the same applications. Strength, modulus of elasticity, impact strength, and other properties vary greatly with type, degree of crystallinity, and their preparations that result in different densities. Their stress-crack resistance and useful service temperature ranges may also vary with type of polyolefin, their crystalline structure, etc.

Polyethylene

PEs is the leading plastic family sold worldwide. These polyolefin materials are relatively inexpensive, easy to process and versatile. They dominate the packaging and disposable fields. There are different types of PEs produced. These TP crystalline structural basic polymers with varied chain length and molecular weight produces very low density (VLDPE), low density (LDPE), low density linear (LDLPE), linear low density (LLDPE), medium density (MDPE), high density (HDPE) ultra high density molecular weight (UHMWPE), etc. Some are flexible, others rigid, and some have low impact strength, whereas others are nearly unbreakable. Some have good clarity, others are opaque, and so on. The service temperatures for PEs range from –40 to 93C (–40 to 200F). In general toughness, excellent chemical resistance and electrical properties, low coefficient of friction, near-zero moisture absorption, and good ease of processing characterize them. They are basically classified according to their density (Tables 2.3 and 2.4).

Table 2.3 Density, melt index, and molecular weight influence PEs performances

PE Property	Density	Melt Index	Molecular Weight
Tensile strength (at yield)	Increases	Decreases	
Stiffness	Increases	Decreases slightly	Decreases slightly
Impact strength	Decreases	Decreases	Decreases
Low-temperature brittleness	Increases	Increases	Decreases
Abrasion resistance	Increases	Decreases	
Hardness	Increases	Decreases slightly	
Softening point	Increases		Increases
Stress-crack resistance	Decreases	Decreases	
Permeability	Decreases	Increases slightly	
Chemical resistance	Increases	Decreases	
Melt strength		Decreases	Increases
Gloss	Increases	Increases	Decreases
Shrinkage	Decreases	Decreases	Increases

There are bimodal high density PEs that are extensively used in Europe. Demand for polyethylene (PE) water pipes in Europe are greater than in USA. Europeans have used upgraded bimodal high density PE since the early 1990s. In USA/Europe ductile iron weight accounted for 49.7%/30.3%, PVC for 46.7%/25%, and PE for 3.6%/44.7 of 2002 domestic water-pressure pipe production. By weight, that production included 2.5/417 billion lb of ductile iron, 2.35/345 billion lb of PVC, and 185/614 million lb of PE. It is reported that it will take more time to convert the North American water utility market to costlier bimodal plastics typically ISO-rated PE100 from today's common monomodal technology. These better PE materials are

Table 2.4 Examples of polyethylene film properties

	Polyethylene				
	Low-density	**Medium-density**	**High-density**	**Linear low density**	**Low density/ EVA copolymer (12% EVA)**
General					
Clarity	Transparent to translucent	Transparent to translucent	Transparent to translucent	Transparent to translucent	Transparent
Yield (sq. In./lb./ 0.001-inch)	30,000	29,500	29,000	30,000	29,500
Specific gravity	0.910-0.925	0.926-0.940	0.941 0.965	.925	0.94
Mechanical					
Tensile strength (lb/sq.in.) ASTM D-882	1,000-3,500	2,000-5,000	3,000-7,500	MD-1540 TD-1620	3000-5000
Elongation (per cent) ASTM D-882	225-600	225-500	10-500	MD-640 TD-680	300-500
Impact strength (kg-cm)	7-11	4-6	1-3	1.3	11-15
Tear strength (gm/0.001-inch Elmendorf) ASTM D-1922	100-400	50-300	15-300	MD-280 TD-400	50-100
Heat seal range (°F.)	250-350	260-310	275-310	250-350	200-300
Chemical					
WVTR (gm/24hr/100 sq. in. @ 100° F. 90 per cent RH) ASTM E-96	1.2	0.5-1.0	0.3-0.65	1.2	3.9
Gas transmission (cc/0.001-inch/100 sq. in./ 24 hr. @ atm 73°F. & 0 per cent RH) ASTM D-1434	O_2-250-840 CO_2-495-5000	O_2-165 335 CO_2-500-840	O_2-33-250 CO_2-250-645	O_2-250-840 CO_2-495 5000	O_2-515-645 CO_2-2260-2900
Resistance to grease and oils	Varies	Good	Good	Good	Varies
Permanence					
Maximum use temperature (°F.)	150	180-220	250	170-180	140
Minimum use temperature (°F.)	−60	−60	−60	−60	−60
Dimension change at high RH (per cent)	None	None	None	None	None

expected to eventually enter into the USA water market. Three domestic makers of advanced HDPE are participating in the Plastics Pipe Institute Inc. (PPI) efforts to expand use of PE water pipe. Meanwhile, manufacturers of gasket-joint PVC and Ductile Iron Pipe, represented by the Uni-Bell PVC Pipe Association of Dallas, TX and the Ductile Iron Pipe Research Association of Birmingham, AL will monitor any market intrusion from PE.

The upgraded bimodal high density PE provides certain advantages. Its excellent ductility enables PE pipe to survive an earthquake better than more rigid materials such as PVC or ductile iron. They have a slow crack growth. PE will not crack under tough tests, but its current design strength is lower than that of PVC for the same pressure rating. That results in PE pipe with a thicker wall structure and excessive cost burden. Even with its advantages its rating for pressure is the biggest single challenge.

Three basic characteristics of PE determine its processing and end-use properties: its density, melt index, and molecular weight (Table 2.3). Their range in density from 0.890 to at least 0.960 g/cm^3 is a result of their crystalline structures (Chapter 1). This difference accounts for their property variations. As one example, reducing PE's crystallinity increases its impact resistance, cold flow, tackiness, tear strength, environmental stress-crack resistance, and heat-seal range. However, decreases occur in stiffness, shrinkage, brittleness temperature, and chemical resistance. The crystalline melting transition (T_m) decreases from a maximum of about 135C (275F) to a low of about 110C (230F) as the degree of crystallinity are reduced. The very low glass transition temperature [T_g = –110C (–166F)] is associated with a good retention of mechanical properties, including flexibility and impact resistance at low temperatures.

PE grades can be classified according to their melt viscosity or melt index, which strongly reflect the molecular weight of the polymer. This is important for processing where different processes often call for different melt viscosities. For example injection molding is generally associated with an easy flowing grade, while thermoforming requires a high melt consistency or viscosity. Molecular weight does not have such a direct effect on solid state properties, but it is established that high molecular weight is often beneficial, for example, in obtaining adequate environmental stress-cracking resistance.

Linear Polyethylene

LPE include ultralow density PE (ULDPE), linear low density PE (LLDPE), high density PE (HDPE), high molecular weight-high density PE (HMWHDPE), and ultra high molecular weight PE (UHMWPE). They polymerized in reactors maintained at pressures far lower than those for making branched PE. In making branched PE the crucial plastic parameter of density is varied through changes in reactor pressure and heat. In turn they relate to the closeness and regularity (or crystallinity) of the packing of the long polymer backbones. However, LPE density varies with the quantity of comonomer used with ethylene. The comonomer forms short chain branches along the ethylene backbone; the greater the quantity of comonomer, the lower the density of the plastic.

Low Density Polyethylene

The first of the PEs during the 1930s was LDPEs, the first of the PEs had good toughness, flexibility, low temperature resistance, clarity in film, electrical insulation, and relatively low heat resistance, as well as good resistance to chemical attack. They are more subject to stress cracking but exhibits greater flexibility and somewhat greater processability. They exhibit good electric properties over a wide range of temperatures.

At room temperature LDPE is insoluble in most organic solvents but attacked by strong oxidizing acids. At high temperatures it becomes increasingly susceptible to attack by aromatic, chlorinated, and aliphatic hydrocarbons. The LDPEs are susceptible to environmental and some chemical stress cracking. For example, wetting agents such as detergents accelerate stress cracking. Some copolymers of LDPE are available with an improved stress-cracking resistance.

The thermal properties of LDPE include a melting range with a peak melting point of 223 to 234F (106 to 112C). Its relatively low melting point and broad melting range characterize LDPE as a plastic that permits fast, forgiving heat-seal operations. The glass-transition temperature (T_g) of LDPE is well below room temperature, accounting for the plastic's soft, flexible nature. The combination of crystalline and amorphous phases in LDPE can make determination of T_g difficult. It is reported that the molecular transitions in LDPEs are about –4 and –193F (–20 and –125C).

Primarily molecular weight (MW) and MW distribution (MWD) affect the mechanical properties of LDPE. The average MW is routinely measured by the melt index or gel permeation chromatography (ASTM D 1238). The high MW results in a low flow rate and low melt index values, so the MW is inversely proportional to the melt index. Such molten state properties of LDPE as melt strength and MW and MWD affect drawdown during processing. Melt strength is an indication of how well the molten plastic can support itself, and drawdown is a measure of how thin the molten plastic can be drawn before breaking. Melt strength is increased with increasing MW and broader MWD, while drawdown is increased with lower MW and narrow MWD. MW and density somewhat influence the mechanical properties of LDPE most by MWD. The melt index and density often have opposite effects on properties, necessitating compromises in plastic selection (Figure 2.1).

MW and density affect the optical properties of LDPE. High MW molecules produce a rough, low gloss surface; HDPEs contain more or larger crystalline areas that scatter light and cause a hazy appearance.

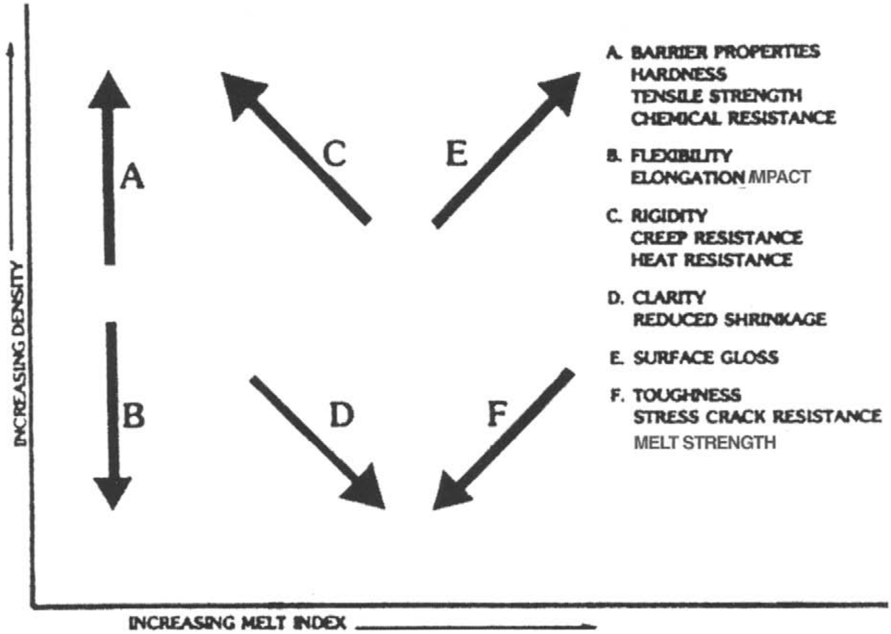

A
B
C
D
E
F
INCREASING DENSITY
INCREASING MELT INDEX
A. BARRIER PROPERTIES
HARDNESS
TENSILE STRENGTH
CHEMICAL RESISTANCE
B. FLEXIBILITY
ELONGATION IMPACT
C. RIGIDITY
CREEP RESISTANCE
HEAT RESISTANCE
D. CLARITY
REDUCED SHRINKAGE
E. SURFACE GLOSS
F. TOUGHNESS
STRESS CRACK RESISTANCE
MELT STRENGTH

Figure 2.1 Example how melt index and density influence PE performances; properties increase in the direction of arrows

Fabrication conditions have a significant effect on optics. Also the environmental properties of LDPE are subject to thermal and ultraviolet degradation. However, additives are available that can extend outdoor service up to several years.

LDPE has a good balance of mechanical and optical properties with easy processability and low cost. It can be fabricated by many different methods for a broad range of applications, making it one of the highest-volume plastics in the world. By comparison, other plastics may excel in a specific property but be restricted to specialty applications by cost, processing limitations, or specific property deficiencies. LDPE may not be suitable for applications that require extreme stiffness, good barrier properties, outstanding tensile strength, or high temperature resistance.

Ultra Low Density Polyethylene

ULDPE is also called very low density PE (VLDPE). It has densities in the range of 0.85 to 0.92 g/cm^3. They provide the flexibility previously available only in generally lower strength materials such as ethylene-vinyl acetate (EVA), ethylene-ethyl acrylate (EEA), and plasticized PVC, together with the toughness and broad operating temperature range of linear low density PE (LLDPE). In addition, ULDPE exhibits sealing and flexibility characteristics comparable to that of 5 to 20%

EVA copolymers, while retaining the physical and mechanical properties of LLDPE.

There are always new ULDPE on the horizon. As an example there is a metallocene catalyzed, very low density polyethylene (mVLDPE) from ExxonMobil Chemical Co., Houston, that offers the excellent toughness associated with mLLDPE plus lower heat-seal temperatures and other advantages over conventional Ziegler-Natta VLDPEs or ULDPEs for flexible packaging. Produced with Exxpol catalyst technology in a gas-phase process plant at Mont Belvieu, Texas, has a density of 0.912 g/cc and MI of 1.0. It is targeted at monolayer and multilayer flexible packaging for meat and dairy products, snacks, prepared convenience foods, frozen foods, etc.[3, 73]

Linear Low Density Polyethylene

LLDPE offers PE having outstanding strength properties. They are used in many application areas including extruded films and coatings, injection molding, and rotational molding. The plastic's density has a significant effect on the flexibility, permeability, tensile strength, and chemical and heat resistance. LLDPE is an extremely versatile adaptable to many fabrication techniques. When comparing LLDPE to conventional LDPE of the same density and melt index in applications, such as films or flexible molded products, they have better impact, tear, toughness, heat-seal strength, or puncture properties, improved environmental stress-cracking resistance (ESCR), chemically inert, and resistant to solvents, acids, and alkalies.

With barrier properties and good dielectric allows them in down gauging of films. Its major uses are for grocery bags, bread bags, sandwich bags, stretch films, shrink-clinging films, industrial trash bags, liners, heavy duty shopping bags, shrink wrap, garment bags, and electrical insulation.[90–93] LLDPE films perform well in packaging applications because of excellent heat-seal strength and hot-tack properties. They can be pigmented and UV stabilized through conventional means. Formulations are available for specific coefficient of friction and blocking resistance requirements.[491]

High Density Polyethylene

The rigidity and tensile strength of HDPE is considerably higher than LDPE and medium density PE (MDPE). Its impact strength in slightly lower, as is to be expected in a stiffer material, but its overall values are high, especially at low temperatures compared to the other TPs. It has a good balance of chemical resistance, low temperature impact strength, lightweight, low cost, and processability.

Other HDPE formulations include a high-flow HDPE that is suited to injection molding thin-wall products like food containers, drink cups, and over-caps. Developed by Equistar Chemicals in Houston, these Alathon resins have a 0.956 density, MI of 56, and higher stiffness than most conventional high-flow HDPEs. Its flexural modulus is 1,170 MPa (170,000 psi). The higher than usual stiffness and crystallization temperature are said to allow shorter molding cycles. Also, it has a lower coefficient of friction, which allows easier part ejection. Faster recovery rates are reportedly attainable due to less screw slippage. While they have a lower MI than typical high-flow HDPEs of 65 to 80 MI, its spiral flow rate is similar, indicating comparable injection performance.

Ultra High Molecular Weight Polyethylenes

UHMWPE has MW at least 10 times that of regular PEs. The polymerization process leads to so-called linear molecules associated with high-density (high crystallinity) PE, although densities (0.926 to 0.940 g/cm^3) correspond to the usual medium crystallinity range (MDPE). The molecular weight must cause such a high degree of physical entanglements that, above the melting point [T_m = 130C (266F)], the material behaves in a rubber-like rather than fluid-like manner causing considerable processing difficulties.

Its outstanding properties qualify them as an engineering plastic. Its chemical inertness is almost not matched and includes environmental stress cracking (ESC) resistance and resistance to foods and physiological fluids. A very important and outstanding property is wear or abrasion resistance. It is associated with the chemical inertness, a very low coefficient of friction, excellent impact resistance (toughness), and fatigue resistance. These properties and a moderate cost explain the growing use of UHMWPE in large scale materials handling equipment (chemical, mining, underwater, etc.), blow molded drums, as well as in many specialized applications (gears, pulleys, pen tips, prosthetic wear surfaces, gears, etc,) using conventional processing methods.

Because of its high melt viscosity it has no useful melt flow index. Conventional screw plasticizing extrusion and injection molding can noy process them. The processing methods used are compression molding, ram extrusion, ram injection, and warm forming of extruded slugs from powdered plastic. In turn many components are machined from semifinished products.

Crosslinked Polyethylene

This is a thermoset plastic; to be reviewed later in this Chapter.

Polyethylene Wax

PE with a molecular weight in the range of 2,000 to 4,000 has the properties of high molecular weight hydrocarbon wax. They have a specific gravity of 0.91 to 0.96, depending on operating conditions.

Melt index is close to 3.5, tensile strength about 1,500 psi (6.9 MPa), melting point of 99 to 100C, and needle penetration test at 25C is 1 to 10. Just over 10wt% of LDPE produced in the USA find use in typical wax applications, such as paper coatings and floor polishes. A major use is coated paperboard for milk cartons.

Chlorinated Polyethylene Elastomers

The moderate random chlorination of polyethylene suppresses crystallinity and yields chlorinated polyethylene elastomer (CPE), a rubber-like material that can be crosslinked with organic peroxides. The chlorine (Cl) content is in the range of 36 to 42%, compared to 56.8% for PVC. Such elastomer has good heat and oil resistance. It is also used as a plasticizer for PVC. They provide a very wide range of properties from soft/elastomeric too hard. They have inherent oxygen and ozone resistance, resist plasticizers, volatility, weathering, and compared to PEs have improved resistance to chemical extraction. Products do not fog at high temperatures as do PVCs and can be made flame retardant.

Polymethylpentene

Major advantages of PMP over other polyolefins are its transparency in thick sections, its short-time heat resistance up to 200C (400F), and its lower specific gravity. It differs from other polyolefins since it is transparent because its crystalline and amorphous phases have the same index of refraction. Almost clear optically PMP has a light transmission value of 90% that is just slightly less than that of the acrylics. It retains most of its physical properties under brief exposure to heat at 200C (400F), but it is not stable at temperatures for an extended time over 150C (300F) without an antioxidant. In a clear form it is not recommended where it will have to undergo long-term exposure to UV environments.

Chemical resistance and electrical properties of PMP are similar to those of the other polyolefins, except that it retains these properties at higher temperatures than do either PE or PP. In this respect PMP tends to compare well with PTFE up to 150C (300F). Molded parts made of this plastic are hard and shiny, yet their impact strength is high at temperatures down to –29C (–20F). Their specific gravity of 0.83 is the lowest of many commercial solid plastics.

Polyolefin Elastomer

POE and polyolefin plastomers (POP) are ethylene alpha olefin copolymers produced using constrained geometry and metallocene catalyst. They differ from traditional polyolefins in that they have narrow molecular weight distribution and a regular placement of the octene co-monomer on the ethylene backbone. This highly uniform distribution allows for some unique plastic characteristics.

Polyolefin Thermoplastic Elastomer

TPEs are blends of various amorphous rubbers such as ethylene-propylene and of polyolefin semicrystalline plastics such as PP. They are part of the family of TP olefins (TPOs). TPOs are mechanical blends consisting of a hard plastic and softer rubber. They are considered different from blends that are dynamically thermoplastic vulcanized (TPV) a process in which the elastomer phase is cured during mixing of the polymers.[84, 94]

Ethylene-Propylene Elastomer

EP elastomers are random, amorphous polymers with outstanding resistance to ozone, aging and weathering, mainly because of the saturated structure in their hydrocarbon backbone. These TPs also possess good low temperature flexibility and heat resistance and have excellent electrical properties. Their resistance to hydrocarbons and solvents is poor. The low density of these elastomers plus their ability to accept very high levels of extender oils and fillers often gives them a cost advantage over other elastomers in many applications. Principal applications are in automotive products, single-ply roofing, thermoplastic olefins and viscosity index improvers for lubricating oils. EP elastomers are the third-largest synthetic rubber consumed worldwide, after styrene-butadiene rubber and polybutadiene rubber. World consumption of EP elastomers in 1998 was about 800 thousand metric tons.

Polypropylene

PPs are in the polyolefin family of plastics representing a major plastic used worldwide providing different performances. They have low specific gravity and good resistance to chemicals and fatigue. PP made with metallocene catalysts (mPP) has improved characteristics such as toughness, stiffness, heat resistance, clarity, barrier properties, high melt flow, and high melt strength.[14, 95] Their densities are slightly lower than PEs but are much stiffer, more heat resistant, and have the same chemical and electrical resistance. They are semi-translucent and milky white in color, with excellent colorability. Their chemical structure makes them stronger than other members of the polyolefin family.

These versatile plastics are available in many grades as well as copolymers like ethylene propylene. NEAT PP has a low density of 0.90, which, combined with its good balance of moderate cost, strength, and stiffness as well as excellent fatigue, chemical resistance, and thermal and electrical properties, makes PP extremely attractive for many indoor and outdoor applications. There are hundreds of formulations that are produced.

PP is widely known for its application in the integral so called living hinges that are used in all types of applications; PP's excellent fatigue resistance is utilized in molding these integral living hinges.[59] They have superior resistance to flexural fatigue stress cracking, with excellent electrical and chemical properties. This versatile polyolefin overcomes poor low temperature performance and other shortcomings through copolymer, filler, and fiber additions. It is widely used in packaging (film and rigid), and in automobile interiors, under-the-hood and underbody applications, dishwashers, pumps, agitators, tubs, filters for laundry appliances and sterilizable medical components, etc.[96]

Electrical properties are affected to varying degrees by their service temperatures. Its dielectric constant is essentially unchanged, but its dielectric strength increases and its volume resistivity decreases as temperature increases.

They are unstable in the presence of oxidation conditions and UV radiation. Although all its grades are stabilized to some extent, specific stabilization systems are often used to suit a formulation to a particular environment, such as where it must undergo outdoor weathering. PPs resist chemical attack and staining and are unaffected by aqueous solutions of inorganic salts or mineral acids and bases, even at high temperatures. Most organic chemicals do not attack them, and there is no solvent for this plastic at room temperature. Halogens, fuming nitric acid, and other active oxidizing agents attack the plastics. Also attacked by aromatic and chlorinated hydrocarbons at high temperatures.

PPs have limited heat resistance, but heat-stabilized grades are available for applications requiring prolonged use at elevated temperatures. The useful life for products molded from such grades may be at least as long as five years at 120C (250F), 10 years at 130C (230F), and 20 years at 99C (210F). Specially stabilized grades are UL rated at 120C (248F) for continuous service. Basically, PP is classified as a slow burning material, but it can also be supplied in flame-retardant grades.

Polybutylene

Part of the polyolefin family are PBs. They are similar to PPs and HDPEs but exhibit a more crystalline structure. This crystallinity produces unusual high strength and extreme resistance to deformation over a temperature range of –10 to 190F. Its structure results in a rubberlike, elastomeric material with low molded-in stress. Tensile stress that does not plateau after reaching its yield point makes possible films that look like PE but act more like polyester (TP) films. Compared to other polyolefins, they have superior resistance to creep and stress cracking. PB films have high tear resistance, toughness, and flexibility. Their chemical and electrical properties are similar to those of the PEs and PPs.

Use includes pipe/tube, packaging, hot-melt adhesives, and sealants. Piping for cold-water use out of PBs has a higher burst strength than pipe made from any other polyolefin. Large diameter pipe has been successfully used in mining and power generation systems to convey abrasive materials. PBs can be alloyed with other polyolefins to provide its inherent advantage. Film made into industrial trash bags gives improved resistance to bursting, puncturing, and tearing.

Cyclic Polybutylene Terephthalate

CBT® plastic is being developed by Dow with target date to have them commercially available by 2005.[422] These plastic polymerize reactively like TSs but have the material properties of a TP. Because its initial viscosity is like water it is easy to process. CBT will provide significant performance improvements over traditional plastics as well as weight reduction, minimized scrap rates, lower tooling costs, and lower processing costs. These cyclics with fiber reinforcements offers stiffness and toughness with a high level of resistance to heat and chemical attack. They are dimensionally stable with low water absorption, provide electrical insulation, and can be made to be flame retardant. Standard composites fabricating processes can be used (injection, compression, thermoforming, etc.). Parts can be welded, adhesively bonded, and painted. Fabricated products are completely recyclable. It is possible to separate them back into their original components without any loss of properties.

Applications include auto products such as vertical and horizontal external body panels, truck boxes and tailgates with Class A high quality surface appearances. Other grades will be available for applications where structural strength is required. Dow predicts many more traditional steel components being made of fiber reinforced plastic (FRP).

Vinyl

Vinyls are one of the most versatile families of plastics. The term vinyl usually identifies the major very large production of polyvinyl chloride (PVC) plastics. The vinyl family, in addition to PVCs, consists of polyvinyl acetals, polyvinyl acetates, polyvinyl alcohols, polyvinyl carbazoles, polyvinyl chloride-acetates, and polyvinylidene chlorides. As a family, they are strong and abrasion resistant. They are unaffected, for the most part, by prolonged exposure to water, common chemicals, and petroleum products. However, they should be kept away from chlorinated solvents, such as many household-cleaning fluids. Vinyls can withstand continuous exposure to heat up to 130F (54C) and perform satisfactorily at food freezing temperatures.[98-105]

Most vinyls are naturally clear, with an unlimited color range for most forms of the materials. They generally have in common excellent strength, abrasion resistance, and self-extinguishable. In their elastomeric form vinyls usually exhibit properties superior to those of natural rubber in their flexural life, resistance to acids, alcohols, sunlight, wear, and aging.

They are slow burning and some types are self-extinguishing but they should be kept away from direct heat. The vinyls may be given a wide range of colors and may be printed or embossed. They generally have excellent electrical properties but with relatively poor weathering qualities are recommended for indoor use only unless stabilized wit suitable additives. Vinyls literally can be processed by more techniques than any other plastic. Reason is that it contains a relatively polar polymer that allows a large range of formations.

Polyvinyl Chloride

The high volume PVCs worldwide market provides a wide range of low cost flexible to rigid plastic with moderate heat resistance and good chemical, weather and flame resistance. The manufacture of a wide range of products is possible because of PVC's miscibility with an amount and variety of plasticizers. PVC has good clarity and chemical resistance (Figures 2.2 and 2.3).

PVC can be chlorinated (CPVC) and be alloyed with other polymers like ABS, acrylics, polyurethanes, and nitrile rubbers to improve its impact resistance, heat deflection, and processability. Although these vinyls differ in having literally thousands of varying compositions and properties, there are certain general characteristics that are common to nearly all these plastics. Most materials based on vinyls are inherently TP and heat sealable. The exceptions are the products that have been purposely compounded with TSs or crosslinking agents are used.

Rigid PVC, so-called poor man's engineering plastic, has a wide range of properties for use in different products. It has high resistance to ignition, good corrosion, and stain resistance, and weatherability. However, aromatic solvents, ketones, aldehydes, naphthalenes, and some chloride, acetate, and acrylate esters attack it. In general, the normal impact grades of PVCs have better chemical resistance than the high-impact grades. Most PVCs are not recommended for continuous use above 60C (140F). Chlorination to form CPVC increases its heat

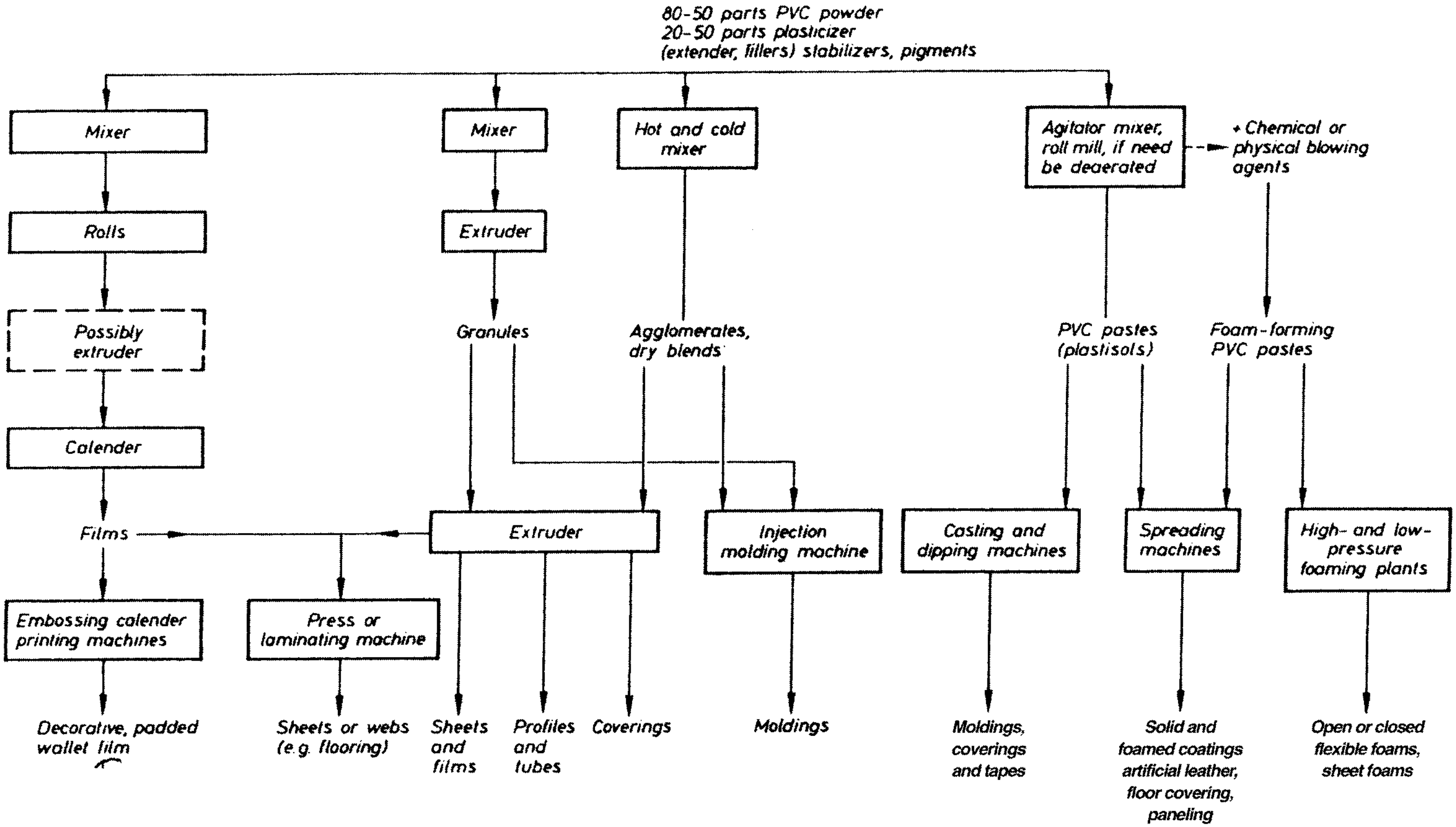

80-50 parts PVC powder
20-50 parts plasticizer
(extender, fillers) stabilizers, pigments
Mixer
Rolls
Possibly extruder
Calender
Films
Embossing calender printing machines
Decorative, padded wallet film
Press or laminating machine
Sheets or webs (e.g. flooring)
Mixer
Extruder
Granules
Extruder
Sheets and films
Profiles and tubes
Coverings
Hot and cold mixer
Agglomerates, dry blends
Injection molding machine
Moldings
Agitator mixer, roll mill, if need be deaerated
+ Chemical or physical blowing agents
PVC pastes (plastisols)
Foam-forming PVC pastes
Casting and dipping machines
Moldings, coverings and tapes
Spreading machines
Solid and foamed coatings artificial leather, floor covering, paneling
High- and low-pressure foaming plants
Open or closed flexible foams, sheet foams

Figure 2.2 Examples of plasticized-flexible PVC

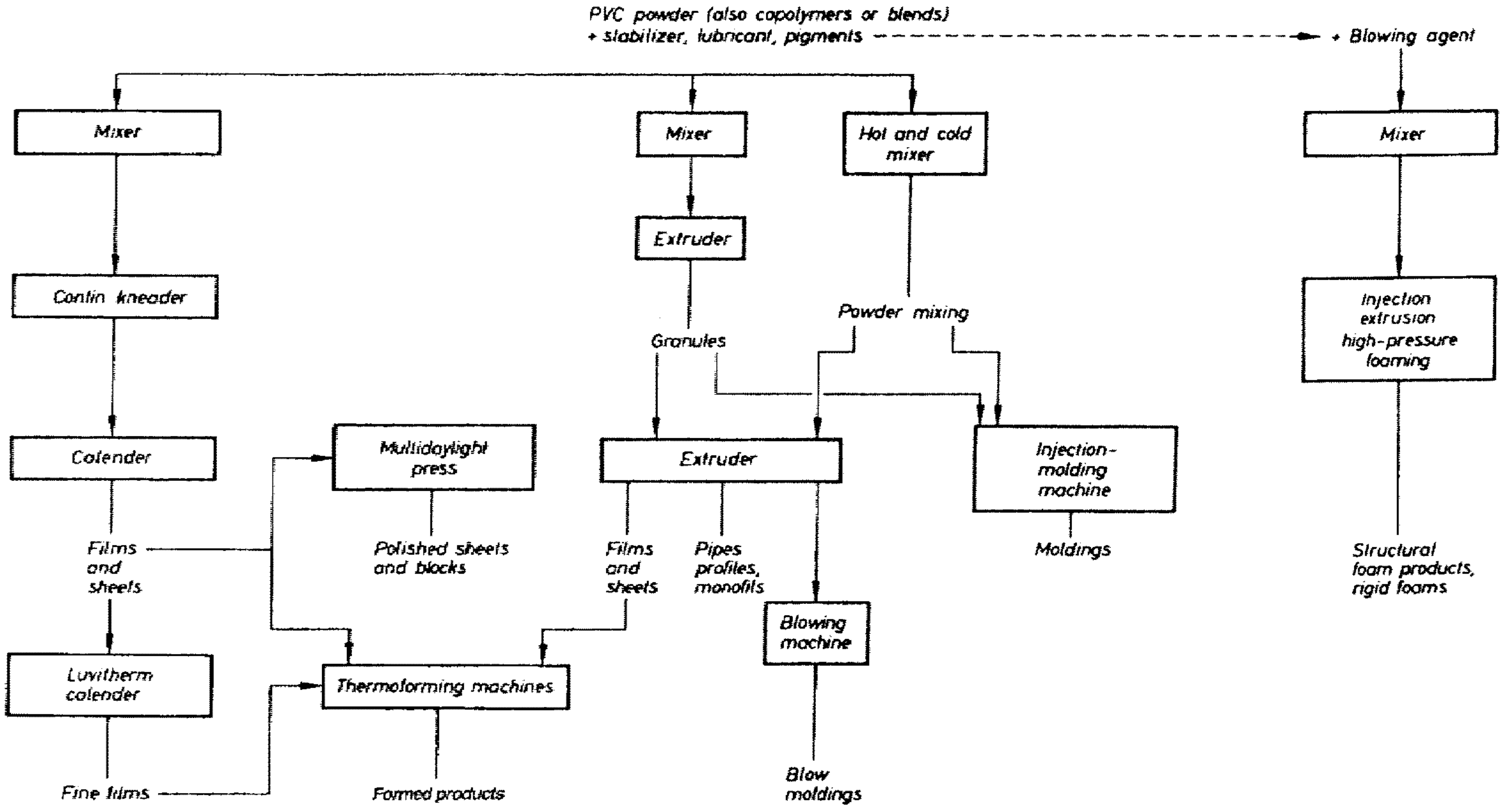

PVC powder (also copolymers or blends)
+ stabilizer, lubricant, pigments
+ Blowing agent
Mixer
Mixer
Hot and cold mixer
Mixer
Extruder
Contin. kneader
Powder mixing
Granules
Injection extrusion high-pressure foaming
Calender
Multidaylight press
Extruder
Injection-molding machine
Films and sheets
Polished sheets and blocks
Films and sheets
Pipes profiles, monofils
Moldings
Structural foam products, rigid foams
Blowing machine
Luvitherm calender
Thermoforming machines
Fine films
Formed products
Blow moldings

Figure 2.3 Examples of rigid PVC

resistance, flame retardancy, and density, depending on the amount of chlorination introduced. In regard to flammability, note that the vinyls release a limited amount of hydrochloric acid during processing.

Different blends can be prepared providing different properties. Blends with non-compatible polymers such as polyolefin elastomers (POEs) are made to blend by using compatibilizers.[143] These flexible PVC blends can be made with no plasticizers resulting in improved properties. They are nontoxic, tasteless, odorless, and suitable for use as packaging materials that will come in contact with foods and drugs, as well as for decorative packaging requiring ordinary protection. The vinyl plastics can be used in printing inks and be effectively used in coating paper, leather, wood, and, in some cases, plastics. In most forms vinyl can be printed.

They qualify in many markets such as for packaging, pipe, outdoor construction products (siding, window profiles, etc), and a host of low-cost disposable products [including FDA-grade medical uses in blood transfusion, storage, etc.[96]]. Foam-vinyl strippables are used for metal parts packaging. These PVC dispersion plastics are applied in liquid form. Foaming takes place during their cure cycle (Chapter 8). PVCs come in a variety of grades, flexible to rigid. They are tough, can be transparent (as in blow molded bottles and jugs), and are also a good alloying plastic to improve properties and reduce costs.

PVCs inherent characteristics generally require special considerations to ensure the best melt processing conditions and the tool will not be damaged (corrode due to hydrochloric acid) by the PVC. One such consideration is specifying the correct tool steel in order to meet products demanding appearances, meet long run production, etc. (Chapter 17).

Ultra High Molecular Weight Polyvinyl Chloride

UHMWPVCs are versatile plastics that can provide superior mechanical properties and be formulated to produce a variety of products. Because changes in formulations or equipment conditions may be required for processing, these plastics are generally used in plasticized applications; it is in highly plasticized uses that they show the greatest advantages in producing compounds with improved properties. They can bring to flexible vinyls improved tensile, modulus, abrasion, and solvent resistance; low and high temperature performance; and retention of properties during aging.

Polyvinyl Acetate

The PVAc copolymers are odorless, tasteless, nontoxic, slow burning, lightweight, and colorless, with reasonably low water absorption. They are soluble in organic ketones, esters, chlorinated hydrocarbons, aromatic hydrocarbons, and alcohols, but insoluble in water, aliphatic hydrocarbons, fats, and waxes. Water emulsions have extended the use of this plastic. Used perhaps most extensively as adhesives, they are also employed as coatings for paper sizing for textiles, and finishes for leathers, as well as bases for inks and lacquers, for heat-sealing films, and for flashbulb linings.

They include vinyl acetate homopolymers and all copolymers in which vinyl acetate is the major constituent (50% or greater). The major PVAc copolymers are vinyl acetate-ethylene (VAE) and vinyl acetate-acrylic ester (vinyl acrylic). Vinyl acetate-versatic acid (vinyl versatate) and vinyl acetate- maleate are major PVAc copolymer emulsions used.

Polyvinyl Chloride Acetate
PVCA is a copolymer of vinyl chloride and vinyl acetate. It is a colorless thermoplastic solid with good resistance to water as well as concentrated acids and alkalis. It is obtainable in the form of granules, solutions, and emulsions. Compounded with plasticizers, it yields a flexible material superior to rubber in aging properties. It is widely used for cable and wire coverings, in chemical plants, and in protective garments.

Polyvinyl Chloride, Chlorinated
CPVC is a plastic produced by the post-chlorination of PVC. Adding more chlorine raises the glass transition temperature of CPVC at 115 to 135C (239 to 275F) and the resultant heat deflection under load from that of PVC at 70C (158F) to a level of 82 to 102C (180 to 219F) depending on formation. CPVC has improved resistance to combustion and smoke generation with higher tensile strength and modulus while maintaining all the good properties that rigid PVC possesses. Traditional uses are hot and cold-water distribution piping and fittings and industrial chemical liquid handling pipe, fittings, valves, and other different applications.

Polyvinyl Alcohol
PVOH (or tradename PVAL) is a crystalline, white powder soluble in water and alcohols. It is characterized by water solubility, low gas permeability barrier, high resistance to organic solvents other than alcohol, and crystallinity when stretch oriented. Crystallinity allows the material to polarize light. A series of hydrolysis levels of the plastic are available that range from room temperature solubility to those not soluble at all. The major applications of the PVOHs are in elastomeric products, adhesives, films, and finishes. Extruded PVOH hoses and tubing are excellent for use subjected to contact with oils and other chemicals. PVOH is used as a sizing in the manufacture of nylon.

Polyvinyl Butyral
PVB is colorless, flexible, very tough solid plastic, soluble in esters, ketones, alcohols, and chlorinated hydrocarbons but insoluble in the aliphatic hydrocarbons. They are stable in dilute alkali; but slowly decompose in dilute acids. Since the year 1930s PVBs have been extensively used as shatterproof safety-glass interlayers and between sheets of acrylic to protect the enclosures of pressurized cabins in aircraft against shattering. PVB film interlayers range from 10 to 40 mils. They continue to be used as an important resource for the building glass windows, automotive. architectural industries, etc. PVBs are also used as coatings for textiles and paper and also as adhesives.

Polyvinyl Carbazole
PVCB is brown in color, obtained by reacting acetylene with carbazole. The plastic has excellent electrical properties and good heat and chemical resistance. Use includes high frequency dielectrics. impregnant for paper capacitors. and photoconductive plastics.

Polyvinyl Pyridine
PVP is primarily used as a constituent in copolymers as adhesives.

Polyvinyl Pyrrolidone
PVPO is highly polar and water-soluble plastic. It finds applications in adhesives and as a water thickener. Water solutions can be used as blood plasma substitute or artificial blood.

Polyvinylfluoride
PVF products are strong and tough, with good abrasion and staining resistance up to fairly high temperatures of 100 to 150C (212 to 302F) and they are classified as slow burning. They are generally less chemical resistant than fully fluorinated plastics but show excellent UV resistance and good color retention and are not affected by water. Their excellent weatherability has made them a choice material for exterior applications such as coatings for metals (slides, gutters, etc.), plywood finishes, architectural sheets, lighting panels, and glazing for solar energy collection. Also for electrical wrapping tape and parting layers for laminates.

Polyvinyl Formal
PVFO finds applications as temperature-resistant coatings for containers and electric wires. It resistant greases and oils.

Polyvinylidene Chloride
There are flexible and rigid PVDCs. They have high strength, abrasion resistance, strong welds, dimensional stability, toughness, and durability. This material is especially suited for injection molding at high speed that provides heavy, thick cross-sections. Molded fittings and

parts are particularly valuable in industries involving the use of chemicals. For example pipes of this material are superior to iron pipes to dispose of waste acids. As an extruded monofilament it is woven into upholstery fabric and screening. Films produced from PVDC exhibit an extremely low water-vapor transmission rate, as well as flexibility over a wide range of temperatures and heat sealability. They are particularly suitable for various types of packaging, including medical products, metal parts, and food. Food packaging for the home refrigerator uses the highly popular Saran (PVDC) wrap from Dow.

Polyvinylidene Fluoride
PVDF is a fluorine-containing TP unlike other plastics. It is a crystalline. high molecular weight polymer of vinylidene fluoride. Compounds are available that contain at least 60wt% fluorine. This nonflammable plastic is mechanically strong and tough, thermally stable, resistant to almost all chemicals and solvents. It is also stable to UV and extreme weather conditions with higher strength and abrasion resistance than PTFE; however, it does not match the high chemical and temperature resistance of PTFE. Where unfavorable combinations of chemical, mechanical, and physical environments may preclude the use of other materials, PVDF has been successfully used. Examples include valve and pump parts, heavy wall pipefittings, gears, cams, bearings, coatings, and electrical insulations. Its limitations include lower service temperatures than the highly fluorinated fluoropolymers, no anti-stick qualities, and the fact that it produces toxic products upon thermal decomposition.

Polystyrene

PS is a high volume worldwide consumed plastic. It is used in many different formulations. PS is noted for its sparkling clarity, hardness, low water absorption, extreme ease of processing general purpose PS (GPPS), excellent colorability, dimensional stability, and relatively low cost. This amorphous TP often competes favorably with higher-priced plastics. It is available in a wide range of grades for all types of processes.

In its basic crystal PS form it is brittle, with low heat and chemical resistance, poor weather resistance. High impact polystyrene is made with butadiene modifiers that provides significant improvements in impact strength and elongation over crystal polystyrene, accompanied by a loss of transparency and little other property improvement. Modifications available to the basic GPPS include grades for high heat and for various degrees of impact resistance. Clarity and gloss are reduced, however, in the impact grades. There are ignition-resistant polystyrenes (IRPSs). Some examples of members in the PS family are compounds of ABS, SAN, and SMA (styrene maleic anhydride). The structural characteristics of these copolymers are similar, but the SMA has the highest heat resistance.

PS is soluble in most aromatic and chlorinated solvents but insoluble in such alcohols as methanol, ethanol, normal heptane, and acetone. Most fluids in households, as well as drinks and foods, have no effect, but the oil in citrus-fruit rinds, gasoline, turpentine, and lacquer attack PS. PSs are available in FDA-approved grades.

Waste that occurs during the manufacturing and processing of PS has practically always been fed/recycled back into the processing cycle. The reuse of municipal waste is feasible without any problems with uncontaminated and contaminated materials. Each is used in new market products.

Polystyrene Copolymer
Copolymers of styrene include a large group of random, graft, and block copolymers. Those with a high proportion of acrylonitrile used in barrier films as well as others such as methacrylic-butadiene-styrene copolymer (MBS) plastic is used as modifiers in PVC, SAN, ABS, ASA, etc. The styrene-acrylonitrile copolymer (SAN) is the most important when considering volume and number of applications.

Polystyrene, Expandable
Popular is expandable polystyrene (EPS) that is a specialized form of PS. Products have low heat resistance, as compared to most TPs. Their maximum recommended continuous service temperature is below 93C (200F). Their electrical properties, that are good at room temperature, are affected only slightly by higher temperatures and varying humidity. EPS is a modified PS prepared as small beads containing pentane gas which, when steamed, expand to form lightweight, cohesive masses for forms used to mold cups and trays, package fragile products for shipment, etc. (Chapter 8). Similar dimensionally stable forms molded from EPS are used as cores for such products as automobile sun visors with surface overlays, etc.

Polystyrene Maleic Anhydride
SMA is a copolymer made with or without rubber modifiers. They are sometimes alloyed with ABS and offer good heat resistance, high impact strength and gloss but with little appreciable improvement in weatherability or chemical resistance over other styrene based plastics.

Crystal Clear Polystyrene
The styrene-butadiene styrene block copolymers with a polybutadiene content of up to 30wt%, which are referred to as crystal clear, impact-

resistant, are completely different from standard impact-resistant PS. These are frequently mixed with standard PS on price grounds and also in order to achieve greater rigidity. Only certain defined grades of standard PS will give a mixture that is crystal clear. These plastics have excellent clarity, gloss, and stiffness, but are very brittle. Crystal PS is sometimes blended with other plastics to optimize physical properties, or coextruded onto impact PS to provide a higher gloss surface.

Flame Retardant Polystyrene
The market for flame retardant PS has been disconcerted by the continuing announcements that TPs containing polybrominated diphenyl ethers can release brominated dioxins or furanes under certain conditions. At the same time as investigations were started into the formation of these compounds and their toxicity, a precautionary substitution of the products in question started. The advantages of these materials, which also contained halogens that improve melt flowability and light stability, do not make up for their drawback of a lower temperature stability in a large number of products. For example, product grades containing polybrominated diphenyl ether are used to meet the UL 94 V-O rating.

Polystyrene Film, Heat-Sealable
PS heat-sealable film has extensive use in different marketable products with its major emphasis in packaging. They produce good sealing seam strength, tear resistance, and tear propagation strength.

High Gloss Polystyrene
High gloss products are available with a medium or high impact strength that incorporate particles of rubber that are several times smaller than for standard impact resistant PS, referred to as capsule or small cell particles, as a function of their structure. With their combination of high gloss, high rigidity, high impact strength, and high heat resistance, which is competitive to ABS's high gloss products, the products have replaced traditional impact resistant PS in different markets.

High Impact Polystyrene
HIPS is PS modified by the addition of rubber such as polybutadiene particles to improve impact strength. Products obtained merely by milling together rubber and PS or by coagulation of mixed lattices of these two materials have inferior impact properties. As the rubber content increases so does the impact strength but correspondingly the softening point and stiffness decrease and the products are no longer transparent. These modified plastics exhibit enhanced impact properties and stress-crack resistance. They are translucent to opaque. End uses

include foamed food trays, packaging, disposable cups, and printed displays.

Syndiotactic Polystyrene
SPS is a crystalline plastic with far higher heat resistance than standard amorphous PS, lower moisture pick-up, and improved warp-resistance, and outstanding dimensional stability (eliminates the need for mineral fillers commonly used to counter warpage in other plastics such as nylon and PBT). It is made with metallocene catalyst technology This plastic has the highest melting point (518F) (270C) of any styrenic homopolymer. It also has high chemical, water, and steam resistance, exceptional electrical properties, and well-balanced impact resistance and stiffness.[10]

Polystyrene-Acrylonitrile
SAN is hard, rigid, and transparent. It has no butadiene as in ABS. Excellent chemical and heat resistance, good dimensional stability, and ease of processing characterize it. Special grades are available that have improved UV stability, vapor-barrier characteristics, and weatherability. SAN is used for tinted drinking glasses, low-cost blender jars and water pitchers, and other consumer goods with longer life expectancies than ordinary PS.

Polystyrene-Polyethylene Blend
The target of combining the lower water vapor permeability and good stress cracking of PE (or PP) with the problem free processing and high rigidity of PS in the past proved to be unattainable, because of their incompatibility. This situation has been reduced through the use of mixing agents made up of styrene/olefin copolymers, etc. PS-PE blends are primarily used as a substitute for PVC and ABS in the form of monofilm or multilayer film to produce thermoformed packaging for foods such as those that contain fat.

Polystyrene-Polyphenylene Ether Blend
The good compatibility of PS and polyphenylene ether (PPE) has been used for a long time to make blends that even with a PS content in excess of 50wt% still count as modified PPE. The addition of PPE results in the increase of PS's heat resistance that can be raised to the same range as that for ABS. Result is a lower cost plastic.

Advanced Styrenic
These ASRs are produced either chemically in a reactor or by blending GPPS and rubber in downstream operations. This family of plastics has good toughness and gloss, and very good processability. ASRs can be processed on conventional sheet extrusion and thermo-forming equipment. They are recommended for applications where intermediate

properties between HIPS and ABS are desired. It has been used in coextruded refrigerator liners where ASR is the cap layer.

Styrene-Butadiene
SB copolymers are produced via anionic polymerization by sequential addition of styrene and 1,3-butadiene monomers. These clear, tough plastics are easily processed with conditions and equipment similar to those used for HIPS. Various amounts of GPPS are usually mixed with the SB copolymers during sheet extrusion to maximize rigidity and economics in the thermoformed parts. Typical applications include drinkware, medical packaging, lids, containers, and blister packages.

Polyalphamethylstyrene
PAMS has no significant commercial importance as a homopolymer inspite of a relatively high glass transition temperature that gives it much better temperature resistance than PS. It finds significant use in copolymers.

Acetal

These crystalline plastics are strong, stiff, and have exceptional resistance to abrasion, heat, chemicals, creep and fatigue.[106] With a low coefficient of surface friction, it is especially useful for mechanical products such as gears, pawls, latches, cams, cranks, plumbing parts, etc. Different formulations are available to meet different requirements.[462]

Acrylic

The acrylic plastics use the term "acryl" such as polymethyl methacrylate (PMMA), polyacrylic acid, polymethacrytic acid, poly-R acrylate, poly-R methacrylate, polymethylacrylate, polyethylmethacrylate, and cyanoacrylate plastics. PMMA is the major and most important homopolymer in the series of acrylics with a sufficient high glass transition temperature to form useful products. Repeat units of the other types are used. Ethylacrylate repeat units form the major component in acrylate rubbers. PMMAs have high optical clarity, excellent weatherability, very broad color range, and hardest surface of any untreated thermoplastic. Chemical, thermal and impact properties are good to fair. Acrylics will fail in a brittle manner, independent of the temperature. They will suffer crazing when loaded at stress about halfway to the failure level. This effect is enhanced by the presence of solvents.

Normally exterior use includes optical lenses, automotive taillights, decorative nameplates, aircraft glazing, illuminated signs, medical devices, etc. Used as an opaque colored sheeting thermoformed to produce an outer coating behind which glass-fiber-reinforced TS polyester plastics are sprayed to produce rigid camper tops, swimming-pool steps, plumbing fixtures with weatherability and repairability reported superior to polyester gel coats. Like plywood, there are outdoor weather resistant grades and indoor nonweather resistant grades.

Acrylic molding powders are used in different processed such as injection, extrusion, and casting. Their mold shrinkage is low. A semiviscous liquid casting syrup may be poured into a mold and cured at temperatures of 150 to 250F to convert it into a hard, rigid solid. Acrylic sheets of excellent clarity are made this way (Chapter 11). Products include siding and shutters, automotive and RV exteriors, tractor canopies, marine and leisure craft parts, sanitaryware, interior decorative panels, spas, glazing, and outdoor signs.

Among the other forms of acrylics, coatings for protecting metal and acrylic enamels for cars and appliances are available in great variety. Water emulsion acrylic paints give excellent service, both indoors and out, and acrylic adhesives are used to bond many carpeting fibers to their backing and provide nonskid properties and dimensional stability.

Acrylic Elastomer
Under the heading acrylic elastomer the plastic literature has included a broad spectrum of carboxy-modified rubbers that have as a minor portion of the comonomers acrylic acid and/or its derivatives. However, in more recent usage the term acrylic elastomer is used to designate these rubbery products that contain a predominant amount of an acrylic ester, such as ethyl acrylate or butyl acrylate in the polymer chain. Fluoroacrylate elastomers are based on plastics prepared from the acrylic acid ester-dihydroperfluoro alcohols.

Polymethacrylic Acid
PMAA is water-soluble and essential in the formation of ionomer plastics.

Polymethylacrylate
PMA is used in adhesives, paints, and other products.

Polyethylmethacrylate
This is a special plastic in the acrylic family; PEMA provides the usual properties with flexibility.

Polyglutarimide Acrylic Copolymer
Family of plastics that can be used in hot fill and retort packaging applications that provide clarity and heat resistance.

Acrylonitrile

ANs are those that contain a majority of nitrile polymers. They provide good gas barrier, chemical resistance, and low taste and odor transfer with good impact properties when modified with rubber. Extruded sheet is used extensively in food packaging and rigid packaging applications. This crystalline TP is most useful in copolymers. Its copolymer with butadiene is nitrile rubber. Acrylonitrile-butadiene copolymers with styrene (SAN) exist that are tougher than PS. It is also used as a synthetic fiber and as a chemical intermediate.

Acrylonitrile-Butadiene Rubber

It is a copolymer with 20 to 50% of acrylonitrile that is a general purpose, oil-resistant rubber that is also called nitrile rubber (NBR). Its resistance to oils, fuels, and solvents is superior to that of polychloroprene (CR). Heat aging is rather good, and abrasion resistance is high. Cost is moderate. Ozone and weathering resistance is not very good, and low temperature flexibility is quite limited in some grades. Applications include fuel and oil tubing and hose, gaskets and seals, conveyor belting, and printing rolls and pads.

Acrylonitrile-Butadiene-Styrene

Popularly used ABS is an amorphous terpolymer composed of acrylonitrile, butadiene, and styrene. These materials are processed by most methods including injection molding, extruding, and thermoforming. They provide a tough, hard, not brittle, rigid plastic with good chemical, electrical and weathering characteristics, low water absorption, resistance to hot-and-cold water cycles, good dimensional stability, high abrasion resistance, and some grades are easily electroplated. Often considered as a modified PS since its properties resemble PS, except that its impact strength is much higher. ABS is used where good appearance and strength, together with reasonable stiffness and softening point are required. A very wide variety of commercial products are available, varying not only in composition but also in morphology due to the different procedures used in copolymer preparation.

ABS usually contains about 20wt% rubber, about 25% acrylonitrile, and about 55% styrene, having a T_g value of about 105C, a tensile modulus of 2.5GPa, and an impact strength of about 4 J $(12.7\ \mathrm{mm})^{-1}$ on an Izod test. However, owing to the many variations possible, the properties can vary considerably. As an example, Super ABS can have a notched Izod impact strength of up to 8 J $(25\ \mathrm{mm})^{-1}$. Also some or all of one of the comonomers may be replaced. Methylmethacrylate may replace acrylonitrile, as in MBS and MABS, with improvement in transparency, or a saturated rubber may replace the polybutadiene, as in ASA and ACS, with an improvement in oxidation resistance.

Uses are extensive such as electronic instrument housings, telephones, sports gear, automotive grilles, furniture, etc. It is electroplatable, good as a structural foam, and available as a tinted transparent. Other applications include luggage, truck caps, spas, RV and automotive interior and exterior panels and trim, appliances, refrigerator liners, table tops and leisure crafts.

Acrylonitrile-Butadiene-Styrene, Transparent

When the refractive indices of the elastomer are matched usually by incorporating methyl methacrylate, transparent products are possible. Progress in product development is achieved by further matching the properties of those of the standard ABS and also by increasing the light transmission up to 88%. Another gain is better processing melt flowability of the products. An example of an application is in products for medical packaging. Other applications include paper feeds for copy machines, watch crystal, transparent building blocks for toy systems, transparent trays for freezers, and packaging for cosmetics.

Acrylonitrile-Chlorinated Polyethylene-Styrene Copolymer

ACS is a terpolymer obtained by the copolymerization of acrylonitrile and styrene in the presence of chlorinated polyethylene. Properties are similar to ABS, except that it is more resistant to embrittlement due to oxidative degradation, and has better fire resistance. It has a very high flame-retardance; ACS is classified as UL 94 V–0 (1⁄16in thick specimen). ACS inherently resists the electrostatic deposition of dust resulting in no need for the addition of antistatic agents to the formulation. The material's deflection temperature under load ranges from 78 to 90C (172 to 194F). Products made of ACS can be adhered to each other, hot stamped and painted, and find their greatest use in cabinets and housings.

Acrylonitrile-Ethylene/Propylene-Styrene Copolymer

AES is a terpolymer obtained by grafting styrene-acrylonitrile copolymer to ethylene-propylene or ethylene-propylene-diene monomer rubber. Similar to ABS except with improved weathering resistance.

Acrylonitrile-Ethylene-Styrene

They are amorphous, opaque, terpolymers produced by suspension, emulsion, or continuous mass polymerization. Properties are similar to ABS, with the addition of weatherability or UV protection for outdoor use. These materials are usually coextruded over ABS. Typically applications have been exterior automotive and RV parts, truck caps, pool steps, outdoor signs, camper shells, and sidings.

Acrylonitrile-Methylmethacrylate
These copolymers use about 70wt% of acrylonitrile and 30% of methylmethacrylate repeat units. ANM are used for thick transparent products, such as glazing, which require high-impact properties and good chemical and weathering resistance.

Acrylonitrile-Styrene
ANS is a high nitrile plastic of styrene-acrylonitrile or other monomer acrylonitrile copolymer with a high acrylonitrile content of about 70 to 80wt%. They are barrier plastics because they have a very low permeability to gases (including carbon dioxide), and liquids. ANS also provide good chemical resistance. They are used in packaging, especially for bottles containing carbonated drinks.

This was the first plastic to produce stretched two-liter Coca-Cola carbonated beverage bottles during 1958; production was by Monsanto Co. using AN plastic "Barex" (Sohia of BP Chemical International) and Du Pont's stretched injection blow molding process.[423] Unfortunately AN, after a successful development project, was not permitted by the FDA to be used because of possible food contamination, thus stopping production in about eight plants on the East Coast including recycling operations. However it was the forerunner of an avalanche of PET containers to appear commercially in the 1970s and continue thereafter. After decades of taxpayers and industries (lots of) money expended, AN was cleared to be used. However in the mean time PET plastic was very successful in its replacement.

Acrylonitrile-Styrene-Acrylate
ASA terpolymer is similar to ABS. This blend improves its resistance to oxidative degradation. It provides UV-resistant resulting in an excellent combination of color and property retention after outdoor exposure in both light and dark colors. There are three major markets for ASA: building and construction, leisure and recreation, and automotive.

Polymethacrylonitrile
PMAN is transparent, is an excellent barrier to carbon dioxide (CO_2), and possesses good creep resistance, making it a suitable material for carbonated beverage containers.

Polyvinylcyanide
PAN homopolymer is not a true TP. It is a polar crystallizing polymer that undergoes chemical decomposition before crystalline melting at temperatures above 300C (572F). The almost pure homopolymer, however, can be processed into fiber (acrylic fibers) through its spinning from solutions (Chapter 6). PAN is also used as a base material

or precursor in the manufacture of certain carbon and graphite reinforcement fibers (Chapter 15).

Cellulosic

These plastics have been used for over a century. They are tough, transparent, hard or flexible natural materials made from vegetable plant cellulose feedstock. With exposure to light, heat, weather and aging, they tend to dry out, deform, embrittle and lose gloss. Molding applications include tool handles, control knobs, eyeglass frames. Extrusion uses include blister packaging, toys, holiday decorations, etc. Cellulosic types, each with their specialty properties, include cellulose acetates (CAs), cellulose acetate butyrates (CABs), cellulose nitrates (CNs), cellulose propionate (CAPs), and ethyl celluloses (EC).

Chlorinated Polyether

CPs is corrosion and chemical resistant. This plastic resists both organic and inorganic agents, except fuming nitric acid and fuming sulfuric acid, at temperatures up to 121C (250F) or higher. Its heat-insulating characteristics, dimensional stability, and outdoor exposure resistance are also excellent. Use has been to manufacture products and equipment for the chemical and processing industries. Uses also include molding components for pumps and water meters, pump gears, bearing surfaces, and the like.

Ethylene-Vinyl Acetate

EVAs (polyolefin copolymer) have exceptional barrier properties, good clarity and gloss, stress-crack resistance, low temperature toughness/ retains flexibility, adhesion, resistance to UV radiation, etc. They have low resistance to heat and solvents as well as exceptional weathering resistance.

Ethylene-Vinyl Alcohol

EVOH have superior gas barrier properties.[80, 89] They are often used as the internal layer in multilayer food packaging films, blow molded rigid containers, gasoline tanks for automobiles for a variety of purposes, etc. EVOH can be fabricated by the usual melt processing methods. The barrier properties of films decrease in the presence of moisture, so multilayer with protective polypropylene (especially biaxially oriented material), low-density polyethylene, nylons, or other moisture barrier films provides films or products that are useful even with liquids. The ethylene contents of commercial ethylene-vinyl alcohol polymer ranges from about 30 to 50mole% (20 to 40wt%) ethylene.

Fluoroelastomer

These elastomers are also called fluorine rubbers. These fluorine-containing plastics are noted for their exceptional resistance to heat, weathering, and a wide variety of fluids and chemicals as well as for their excellent sealing and mechanical properties. They are used in highly demanding applications where extreme temperature ranges and chemical attacks are encountered. The chief limitations on the use of fluoroelastomers are cost and the relatively different technology of compounding and curing, which may involve long postcures.[107–109]

Cured products generally have fairly low-temperature flexibility and low resilience. Solvent resistance is usually high; however, certain organic liquids can cause considerable swelling. In addition they are very sensitive to moisture and require a strictly controlled environment to process, thereby making the processing of fluoroelastomers difficult to handle when compared to conventional commodity plastics; processing requires the usual process control used when fabricating plastics that require tighter controls than the usual plastics.

They are used in a variety of demanding applications in such industries as transportation, chemical/food processing, electrical/electronics, and aviation/aerospace. Environmental concerns in automotive exhausts are driving the growth of these compounds. Components made with these materials are becoming increasingly popular in sealant applications because they can withstand temperatures of car engines (which have been increasing in recent years) and the corrosive nature of fuel and engine fluids. As automotive manufacturers require long lasting components, demand for fluoroelastomers will increase.

Fluoroplastic

The family of FPs, also called fluorocarbon plastics, is based on polymers made of monomers composed of fluorine and carbon; may also include chlorine atoms in their structure. Specific types include polytetrafluoroethylene (PTFE), polytetrafluoroethylene-cohexafluoropropylene or fluorinated ethylene propylene (FEP), polytrafluoroethylene-coperfluoropropylvinyl ether (PFA), ethylenetetrafluoroethylene (ETFE). polychlorotrifluoroethylene (PCTFE), ethylene-chlorotrifluoroethylene (ECTFE), polyvinylidene fluoride (PVDF), polyvinyl fluoride (PVF), perfluoromethylvinylether (PFMV), perfluoroalkoxy (PFA), etc.

Their common properties are outstanding chemical inertness, resistance to temperatures from –220C (–425F) to as high as 260C (500F), low coefficient of friction, good electric properties, low permeability, practical zero moisture absorption, and good resistance to weathering and ozone. They have only moderate strength. There are amorphous and crystalline FPs: perfluoroplastic and fluoroplastic with stabilized end groups that enhance surface properties and advances processing. Figure 2.4 provides examples on properties influenced by fluorine content in fluoroplastics. Their mechanical properties normally are low, but change dramatically when the fluorocarbons are reinforced with glass fibers, molybdenum disulfide fillers, etc.

LOW FLUORINE CONTENT	Properties	HIGH FLUORINE CONTENT
	←Coefficient of Friction—	
	←Adhesive Character—	
	—Thermal Stability→	
	—Mechanical Strength at High Temp.→	
	—Softening Temperature→	
	—Antistick→	
	←Cohesive Forces—	
	—Creep→	
	←Dielectric Constant—	
	—Chemical Resistance→	
	—Solvent Resistance→	
	←Mechanical Strength at Ambient Temp.—	
	—Permeability→	
	←Processing Ease—	
	—Oxidative Stability→	

Designations	
PTFE or TFE	Poly tetrafluoroethylene
FEP	Copolymer of hexafluoropropylene and tetrafluoroethylene or fluorinated ethylene propylene
CTFE or PTFCE	Polychlorotrifluoroethylene
PVF	Polyvinylfluoride
PVF_2 or PVDF	Polyvinylidenefluoride
ETFE	Copolymer of ethylene and tetrafluoroethylene
ECTFE	Copolymer of ethylene and chlorotrifluoroethylene
PFA	Polyperfluoroalkoxyethylene

Figure 2.4 Guide to fluoroplastic properties

The higher performing fluoroplastics can not be processed by the usual procedures since they have very low melt flow behavior (non-melt processable FPs). When modified, they can use conventional fabricating processes.[110] As an example PTFE is extremely difficult to process via melt extrusion and molding. It is processed like a ceramic. The material usually is supplied in powder form for compression molding, ram extrusion, ram injection molding, and sintering or in water-based dispersions for coating and impregnating. Each individual type of operation has its own specific method, such as billet molding and skiving, sheet molding, automatic preforming and sintering, ram extrusion, etc. Extensive information on properties of fluoroplastics compared to other plastics is available.

Polytetrafluoroethylene

Popular highly crystalline PTFE or TFE has a unique position in the plastic and other industries due to its chemical inertness, heat-resistance [288C (550F)], excellent electrical insulation properties, remarkable lubricity, and low coefficient of friction in a wide temperature range. PTFE is extremely resistant to attack by corrosive reagents or solvents. Only alkali metals (either molten or dissolved in liquid ammonia) have been found to attack the plastic, presumably by removing fluorine atoms from the chain. For all practical purposes the plastic is unaffected by water and its thermal stability is such that its electrical and mechanical properties do not change for long intervals (months) at temperatures as high as 250C.

Electrical applications include wire and cable insulation, insulation for motors and generators, and high frequency electronic uses. Chemical equipment such as gaskets, pump and valve packing, and valve parts are also fabricated. Low friction and anti-stick applications include non-lubricated bearings and linings for bakery trays and home and institutional food processing equipment.

Polychlorotrifluoroethylene
The repeat unit of PCTFE differs from that of PTFE by the replacement of a fluorine atom by a chlorine atom, which reduces the flexibility of the chains (higher glass transition temperature), their tendency to crystallize (maximum 40 to 65%), and reduce melting point. PCTFE can be made optically clear, an amorphous-like characteristic, in thickness as high as 3 mm (⅛ in.). The reduced melting point and a generally lower molecule weight (100,000 to 200,000) make it a true TP. It has better mechanical properties than PTFE (stiffer, stronger, etc.), but its frictional properties do not come near those of PTFE.

It has extremely low water vapor transmission, even with extruded thin transparent film. Chemical resistance is generally good, although not comparable to PTFE and other fluoroplastics. Chlorinated solvents, in particular, can affect PCTFE, and it can be subjected to stress cracking at elevated temperatures. The presence of chlorine atoms, used to enhance flame retardancy, keeps PCTFE in the nonburning category with PTFE. It causes, however, a serious increase in dielectric losses, particularly at high frequencies.

Processing PCTFE is by the conventional methods (extrusion, injection, etc.); processing temperatures are high, and any degradation of PCTFE can cause severe corrosion and environmental problems. Applications include wire and cable insulation, electronic flexible printed circuits, packaging material (transparent film and sheet), pharmaceutical industry in particular strip and blister packs for tablets and capsules, etc. In the chemical industry, used as gaskets, 0-rings, valve seats, chemical tank liners, etc.

Polyhexafluoropropylone
PHF has a repeat unit corresponding to a fully fluorinated polypropylene repeat unit and is significantly more rigid than the PTFE repeat unit with a glass transition temperature about 11C (52F).

Polyvinyl Fluoride
PVF is commercially available in the form of a tough but flexible film. It has outstanding chemical resistance and excellent outdoors weatherability and maintains its strength from –180 to 150C (–292 to 302F). It has low permeability to most gases and vapors and resists abrasion and staining. Moldings and fibers by conventional processes can be made from PVF but the major application of the material is in the building industry as a protective coating bonded to wood, metal, or asphalt-based materials in 0.001 to 0.002 in. thickness. PVF can outlast most paints, enamels, or other surface coatings.

Polyvinylidene Fluoride
PVDF has a melting point of about 170C (338F). It has good strength properties and resists distortion and creep at both high and low temperatures. PVDF has very good weather, chemical, and solvent resistance. Conventional extrusion, compression molding, and injection molding can process the material. Uses include as a coating, gasketing, and wire and cable jacketing material.

Fluorinated Ethylene Propylene
FEP is closely related to PTFE but has a lower melt viscosity and may therefore be processed by conventional processes and possesses most of the PTFE properties. It is a tough, resilient material with an Izod impact value of 2.9 ft-lb/in. at –70F, no break at 73F, and 95,000 ft-lb/in. at 170F. FEP is noninflammable and melts at 545 to 563F. It has excellent chemical and solvent resistance and is largely used in such electrical applications as terminal blocks and valve and tube holders. FEP is also used for a variety of non-stick applications in food processing equipment.

FEP, like PTFE, degrades when exposed to high-energy radiation with a resultant adverse effect upon properties. At elevated temperatures it can be crosslinked by use of ionizing and ultraviolet radiation. With the introduction of crosslinking reactions, two types of resin became available. With small amount of crosslinking melt-processing is altered due to a changed distribution of MWs. The other type is crosslinked to the extent that it is incapable of melt processing and, in general, has the high temperature properties associated with PTFE.

Chlorofluorohydrocarbon
It is a plastic made from monomers composed of chlorine, fluorine,

hydrogen, and carbon providing improved chemical/strength performance.

Polyfluoroalkoxyphosphazene
PNF achieved its first mass-production applications in the automobile industry. Although its heat resistance is less than that of FPM, this is offset by its considerably better low temperature flexibility. It has good resistance to fuels.

Ionomer

They are in the polyolefin family. Performances include being extremely tough, very high tensile strength, excellent abrasion resistance, and outstanding transparency. Clarity, strength, and good adhesion of films to metal surfaces are the important properties that have led them into its widespread use in food packaging, coatings, film, and sheet using conventional processes. Often used as a heat-seal in multilayer products (coextruded films, laminated, etc.). Ionomers have a relatively low softening point (160F) but offer high resistance to stress cracking and a constant dielectric loss over their useful temperature range [–160 to 160F (–107 to 71C)].

Nylon (Polyamide)

Nylons chemically known as polyamides (PAs) were the first of the TP engineering plastics during the 1930s. They were originally developed as high-strength textile fibers for women stockings. There are different types available for use in different products. The usual numerical classification is based upon the number of carbon atoms in the polybasic acid and the polyfunctional amines. Nylon 6/6, for example, is polyhexamethyleneadipamide. They contain an amide group as a recurring part of the chain and are produced by condensation polymerization (Chapter 1). Nylons exhibit good chemical resistance and toughness and retain their physical properties over a wide range of temperatures. They also have good surface lubricity, slippery, with good electrical properties, but hygroscopic and with dimensional stability lower than most other engineering types. These crystalline plastics, including the more recent developments of amorphous transparent types, are available for processing by different methods.

Property comparisons among the commercial grades of different nylons vary widely because many formulations are available. In general they all have excellent fatigue resistance, low coefficient of friction, good toughness (depending on their degree of crystallinity), and resist a wide spectrum of fuels, oils, and chemicals. Mechanical and other properties of nylons are increased at room and elevated temperatures by incorporating glass fibers (Chapter 15). They have good resistance to creep and cold flow as compared to many of the less rigid TPs. Usually creep can be accurately calculated using apparent modulus values.[1] They also have outstanding resistance to repeated impact. Nylons can withstand a major portion of a breaking load almost indefinitely.

All nylons are inert to biological attack and have electrical properties adequate for most voltages and frequencies. The crystalline structure of nylons that can be controlled to some degree by processing affects their stiffness, strength, and heat resistance. Low crystallinity imparts greater toughness, elongation, and impact resistance but at the sacrifice of tensile strength and stiffness.

All nylons absorb moisture if it is present in the application's environment. An increase in moisture content decreases a material's strength and stiffness and increases its elongation and impact resistance. Type 6/6 nylon usually reaches equilibrium at about 2.5wt% moisture when the relative humidity (RH) reaches 50%. The equilibrium moisture at 50 RH in nylon 6 is slightly higher. In general, nylon's dimensions increase by about 0.2 to 0.3% for each 1% of moisture absorbed. However, performing moisture conditioning prior to putting products into service can compensate for dimensional changes caused by moisture absorption. Such formulations as 6/12, 11, and 12 are considerably less sensitive to moisture than others.

Nylon 6/6 is the most widely used, followed by nylon 6, with similar properties except that it absorbs moisture more rapidly and its melting point is 21C (70F) lower. Also, its lower processing temperature and less crystalline structure result in lower mold shrinkage. Nylon 6/6 has the lowest permeability by gasoline and mineral oil of all the nylons. The 6/10 and 6/12 types are used where lower moisture absorption and better dimensional stability are needed. Nylons 11 and 12 have better dimensional stability and electrical properties than the others because they absorb less moisture. These more expensive types also are compounded with plasticizers to increase their flexibility and ductility. With nylon toughening and technology advancements supertough nylons became available. Their notched lzod impact values are over 10 J/m (20 ft-lb/in), and they fail in a ductile manner.

A new class of semi-aromatic, high-temperature nylons and their compounds has been introduced (Japan's Kuraray Co. Ltd.) called Genestar PA9T. They compete in cost-performance with nylons 6/6 and 4/6, other high temperature nylons and polyphthalamides, PPS, and LCP. PA9T is reported as a poly 1,9-nonamethylene terephthalamide. It is described as unique because it is a homopolymer, has semi-aromatic cores, and has a longer (nine-carbon) hydrocarbon chain structure than other high temperature nylons, which are based on PA6T (six-carbon) structures.

There are liquid castable monomers (not the usual solid) that polymerize and become solid at atmospheric pressure. From these nylons complex products several inches thick and weighing hundreds of pounds can be cast. Another castable liquid monomer is a moldable transparent material. This amorphous type offers better chemical resistance than other thermoplastics that are transparent.

Parylene

The melting point of these plastics ranges from 290 to 400C (554 to 752F), and T_g from 60 to 100C (14 to 212F). As films they exhibit excellent barrier properties against gases and moisture. Their cryogenic performances are excellent. Physical properties are unaffected by thermal cycles from 2K to room temperature. Good thermal endurance in air, absence of air, and inert atmosphere. They are generally insoluble up to 150C (302F). Weather resistance is poor. Thermal stabilities are good but not exceptional. In an inert atmosphere they can provide long-term service up to 220C (428F) and short-term service to 350C (662F). However, service temperatures below about 80C (176F) are more realistic in air. Under cryogenic conditions, they show excellent flexibility at –200C (–328F) and good electrical insulation properties near absolute zero. The electrical properties also remain good at elevated temperatures even after the mechanical properties begin to degrade.

Phoenox

These are high molecular weight TP polyesters based on bisphenol-A and epichlorohydrin; outgrowth of epoxy plastic. There are TPs and via chemical crosslinking become TSs. Performancewise they have moderately good impact resistance, relatively high strength, and good elongation and creep resistance. Their permeability, particularly to oxygen and other gases, is the lowest of any melt-processable plastic. Oxygen permeability is one-twentieth that of HDPE and their moisture-vapor transmission is about the same as that of rigid PVC, higher than PE but much lower than the styrenes. Their color retention, UV resistance, and weatherability are generally poor. They have limited thermal exposure with a recommended operating temperature range from –60 to 80C (–76 to 176F). Phenoxy resins are resistant to acids and alkalis, have poor solvent resistance (especially in ketones) but good resistance to aliphatic hydrocarbons, and resist staining from common household agents rather well.

They are exceptionally useful in primer plastic applications where drying speed, compatibility with various kinds of topcoats, and high adhesive strength is required. Phenoxies are used in automotive and marine primers as well as in heavy-duty maintenance primers. Important use is as a vehicle for coating formulations.

Polyallomer

They exhibit rigidity and high impact strength combined with lightweight (density of 0.902). Properties are similar to those of HDPE and PP. The material provides the greatest yield per pound of any noncellular commercial plastic. The useful temperature range of the polyallomers is –40 to 210F (–40 to 99C). Both frozen food and heat-sterilizable containers can be made from the material. Surface hardness is slightly less than that of PP but its abrasion resistance is greater. Polyallomer is superior to linear PE in processability and stress-crack resistance.

Polyamide

See **Nylon.**

Polyamide-Imide

PAIs are engineering thermoplastics providing excellent dimensional stability, high strength at high temperatures [continuous use at temperatures of 260C (500F)], and good impact resistance. Different grades are available from BP-Amoco (Torlon) such as general purpose, injection moldable, PTFE/graphite wear-resistant compounds, 30% graphite-fiber reinforced compounds, 30% glass-fiber reinforced components, and so on. The room-temperature tensile strength of an unfilled PAI is about 192 MPa (28,000 psi), its compressive strength about 220 MPa (32,000 psi). At 232C (450F) its tensile strength is about 65 MPa (9,500 psi), or as strong as many engineered plastics at room temperature. Continued exposure at 260C for up to 8,000 h produces no significant decline in its tensile.properties.

The unfilled grade of PAI is rated UL 94 V-0 at thicknesses as low as 0.008 in. and has an oxygen index of 45%. PAIs are extremely resistant to flame and have quite low smoke generation. Some reinforced grades have surpassed the FAA requirements for flammability, smoke density, and toxic gas emission. PAIs radiation resistance is good with a tensile strength that drops only about 5% after exposure to 110^9 rads of gamma radiation. Its chemical resistance is very good, virtually unaffected by the aliphatic and aromatic hydrocarbons as well as halogenated solvents and most acid and base solutions. PAI is attacked, however. by some acids at high temperatures, by steam at high pressure and temperatures, and by strong bases. PAI moldings absorb moisture in humid environments or when immersed in water but the rate is low and the process reversible. For example, at 50% relative humidity and 23C (73F) PAIs absorb about 1% weight in 1,000 h. Parts can be restored to their original dimensions by drying.

Polyarylate

PARs are a form of aromatic TP polyester (amorphous) exhibiting an excellent balance of properties such as stiffness, UV resistance, combustion resistance, high heat-distortion temperature, low notch sensitivity, and good electrical insulating values. Uses include for solar glazing, safety equipment, electrical hardware, transportation components, and in the construction industry. They are used primarily in electronic/electrical and automotive applications. Examples are light housings and reflectors. They also find use in microwave cookware, exterior lighting, and safety/medical equipment.

Polyaryletherketone

The family of PAEK plastics is a leading material among the high-temperature stable TPs. It can be highly stressed thermally and mechanically. In certain applications they provide cost and processing advantages when compared with the temperature-stable TSs and fluoropolymers. It allows continuous operating temperature of 250C (480F) and, depending on the type of short-term load, up to 350C (662F). Without additives it has a UL 94 V-0 fire rating down to a test specimen thickness of 0.030 in. The density of PAEK fumes in a fire is the lowest of the TPs. and it has exceptionally low corrosive and toxic fumes. The quantity of heat released upon the outbreak of a fire is quite low and it meets aviation regulations for interior use. PAEK has high hydrolysis resistance and good resistance to many different chemicals.

The properties of this family of plastics include a tensile strength at break of 85 MPa (12,300 psi), an elongation at break of 56%, a tensile modulus of elasticity of 0.6×10^6 psi, a tensile stress at yield at 23C (74F) of 104 MPa (15,100 psi), and at 160C (320F) of 37 MPa (5,400 psi), an elongation at yield of 6% at 23C (74F) and of 2% at 160C (320F), and no break using an unnotched Izod impact test.

PAEKs are plastics in which phenylene rings are linked together via oxygen bridges [ether and carbonyl groups (ketone)] and may be viewed as the family name of this class of plastics. Their ratio influences the glass transition temperature (T_g) and the melt temperature (T_m) of the polyether ketones. They also differ in features that are of such as heat resistance and processing temperature. As an example, a high ketone content leads to a higher T_g and a higher (T_m). Various complicated configurations can be obtained, such as polyetherketoneetherketoneketone (PEKEKK). Others include PEEK, PEK. PEEKK, and PEKK.

Polyarylsulfone

PAS most outstanding property is resistance to low and high temperatures from –240 to 260C (–400 to 500F). It also has good impact resistance, resistance to chemicals, oils, and most solvents, and good electrical insulating properties. It can be processed by conventional fabricating methods (injection, extrusion, ultrasonic welding, etc.).

Polybutylene Terephthalate

PBTs is in the family of TP polyester plastics with excellent engineering properties. They resist moisture, creep, fire, fats, and oils. Marginal chemical resistance exists. Molded items are hard, bright colored, and retain their impact strength at temperatures as low as –40F (–40C). PBT can crystallize much faster than PET. The properties of the highly crystalline PBT (as much as 60%) are fairly similar to unoriented crystalline PET; PBT is not as conveniently oriented as PET.

PBTs offer high strength and rigidity, excellent electrical properties and chemical resistance, rapid molding cycles, and excellent reproducible mold shrinkage. Due to low moisture absorption rates they have excellent dimensional stability. Notched Izod impact strength ranges from 1.0 ft-lb/in. (53 J/m) for unreinforced grades to 3.5 and 16.0 ft-lb/in. (187 and 854 J/m) for reinforced and impact-modified unreinforced grades. Glass reinforced PBT provides good resistance to creep at both ambient and elevated temperatures. PBT not reinforced has a tensile strength of 8,000 psi (55 MPa). With 40wt% glass reinforcement, tensile strength increases to 21,300 psi (147 MPa). Corresponding flexural moduli are 330,000 psi (2280 MPa) and 1,500,000 psi (10,340 MPa), respectfully. Mineral-filled and mineral/glass-filled grades provide intermediate strength and stiffness.

The electrical properties of PBT are stable over a wide range of temperature and humidity. They are good insulators; volume resistivity is greater than 10^{16} ohm-cm. Arc resistance and dielectric strength are high; the dissipation factor low. The different grades of PBT are rated UL 94 HB. Grades are available to meet UL 94 V-0 requirements, and many of them also meet the more restrictive flammability requirements of UL 94 5V. Strength, stiffness, and better thermal properties are gained by reinforcing PBT with glass fibers. If very low warpage is desired, reinforcement with mineral or mineral/glass fillers is used.

Water absorption is less than 0.1wt% after 24 hours. However, PBT is not recommended for extended use in water or aqueous solutions above 52C (125F).[112] PBT plastics are also intrinsically resistant to detergents, weak acids and bases, aliphatic hydrocarbons, fluorinated hydrocarbons, alcohols, ketones, ethylene glycol, carbon tetrachloride, oils, and fats at room temperature. They also exhibit good resistance to motor oil, gasoline, transmission fluids, and brake fluids at temperatures to 60C (140F).[113]

Fast crystallization rate enhances moldability, producing smooth surfaces that can be painted, printed, and ultrasonically welded. UL temperature indexes are relatively high because of a 227C (440F) melting point and a 40C (104F) glass-transition temperature. Unreinforced PBT has a heat-deflection temperature of 154C (310F) at 66 psi (0.5 MPa). Aside from improving strength and stiffness, glass reinforcement also enhances thermal properties, making possible heat-deflection temperatures to 217C (422F).

PBT are used in many types of products such as appliances, automobiles (louvers, under-the-hood electricals, mechanical parts, etc.), electrical and electronic parts, industrial components, consumer items, and so on.

Polycarbonate

PC exhibits excellent clarity and impact strength, plus high heat deflection temperature. They represent over 50wt% of all engineering plastics consumed worldwide.[114] Most PCs can exist individually in various other materials. Different grades of PCs provide specific properties and processing characteristics; different processes are used. These include the flame retardant and reinforced grades, resistance to weather and UV radiation, EMI and RFI shielding, FDA-approved grades for use in food-contact and medical applications.

PCs are very ductile and are self-extinguishing, have heat deflection temperatures (264 psi load) of 130 to 138C (266 to 280F), and can withstand continuous service at temperatures up to 122C (250C). The electrical properties remain relatively constant over a wide range of temperatures and humidity. They resist water, acids, and oxidizing and reducing agents but can be dissolved in aromatic and chlorinated solvents. Typical mechanical properties for the PCs include tensile strength of 55 to 65 MPa (8000 to 9500 psi), tensile modulus of 24 × 10^5 kPa (3.5 × 10^5 psi), and flexural strength of 90 MPa (13,000 psi). They are moldable at 249 to 300C (480F) into parts having very close tolerances, and which are exceptionally dimensionally stable and machinable.

They are tough, heat and flame resistant, dimensionally stable, withstands boiling water, but is less resistant to weather and scratching than acrylics. It is notch-sensitive and has poor solvent resistance in stressed molded products. Thick unreinforced PC resists breakage at temperatures down to –54C (–65F). Grades are available to provide high impact strength, based on different thicknesses at room temperature and a notched Izod impact strength of 6.4 to 8.5 J/cm (12 to 16 ft-lb/in). Even in thick sections, a properly designed PC product has more impact strength at –54C (–65F) than most plastics generally do at RT. Many plastics are not tough at 18C (65F), but there are plastics that are tough even at much lower temperatures. Creep resistance, which is already excellent throughout a broad temperature range, can be further improved by a factor of two to three when PC is reinforced with glass fibers.

Electrical properties (insulation, etc.) are excellent and remain almost unchanged by temperature and humidity conditions. One exception is arc resistance where PCs is lower than in many other plastics. They are generally unaffected by greases, oils, and acids. Water at RT has no effect, but continuous exposure in 65C (150F) to water causes gradual embrittlement. They are soluble in chlorinated hydrocarbons and attacked by most aromatic solvents, esters, and ketones, which cause crazing and cracking in stressed products. Grades with improved chemical resistance are available, and special coating systems can be applied to provide additional chemical protection.

Extruded/thermoformed sheets are used in many applications such as vandal-resistant glazing, display signs, business machine housings, toys, medical parts,[96] and recreational vehicles. Applications are extensive, emanating into all types of markets. Examples would include electronic connectors, switches, terminal blocks, computer disc packs, storage modules and housings, power-tools, blood oxygenators, coffee makers, food blenders, automobile lenses, safety helmets, lenses, many non-burning electrical applications, etc. They offer resistance to bullets and thrown projectiles in glazing for vehicles, buildings, and security installations.

Polycyclohexylenedimethylene terephthalate

PCT is a high temperature plastic that differs from other TP polyesters by its higher heat deflection temperature. They exhibit low moisture absorption and outstanding chemical resistance to a wide variety of chemicals. They can be flame-retarded to achieve UL 94 VO recognition down to a thickness of 1⁄16 in. (1.6 mm). Different copolyesters of PCT exhibit a wide range of properties depending on particular copolyester incorporated.

Polyelectrolyte

These macromolecular compounds when dissolved in a suitable polar solvent (generally water) instantly acquire or can be made to acquire large number of elementary electrical charges distributed along the macromolecular chain. In the former case and when the charge that appears spontaneously has its maximum value, these macromolecules are termed low molar-mass (LMM) electrolytes and in other cases weak polyelectrolytes.

Polyester, Thermoplastic

This family of polyesters has widely varying and important range of properties.[116] There are the two major groups of the TPs with comparatively high melting points and the TSs which are usually typified by a crosslinked structure. TP polyesters are often called saturated polyesters to distinguish them from unsaturated polyesters that are the TSs. (TS polyesters will be reviewed later in this chapter.) Saturated plastics includes TP general polyesters, polyalkylene terephthalates (PATs), polycyclohexanedimethanol terephthalates (PCTs), PCT acid-modified (PCTAs), PET glycols-modified (PETGs), liquid crystal polymers, and the large production materials polybutylene terephthalates (PBTs) and polyethylene terephthalates (PETs). Details on these plastics are included in this chapter.

Polyester Reinforced Urethane

They are poromeric microporous material that have a urethane impregnation or a silicone coating for shoe uppers and industrial leathers.

Polyester Water-Soluble

Water soluble polyesters (WSPs) are important in the surface coatings industry. These non-solvent plastics provide ease of application, ease of cleanup, freedom from toxicity, and freedom from flammability when compared to conventional solvent based paint. They can be utilized as hydrophilic plastics in paper coating and textile coating. In most surface coatings, clear or pigmented solutions arc converted to water-in-soluble coatings by condensation or oxidative polymerization. Their largest use is in surface coating as pigmented electrodeposition and conventional dipping primers. Other applications include sprayed primer-surfaces, semi-gloss trade-sales paints, coil-coating vehicles, and enamels applied by dip, flow-coat, electrodeposition, and spray methods.

Polyetherketone

PEK is heat stable (see **Polyaryletherketone**). As a member of the ketone family it shares with PEEK good chemical resistance; exceptional toughness, strength, rigidity, and load-bearing capabilities; good radiation resistance; the best fire safety characteristics of any thermoplastic, and the ability to be easily melt processed.[117] Super PEKs designed for advance composites have a continuous-service temperature rating of 260C (500F), a glass transition temperature (T_g) of 200C (400F), and a slow crystallization rate that suits them for processes with slow rates of cooling from the melt.

Polyetheretherketone

PEEKs are high-temperature engineering plastics used for high performance applications such as wire and cable for aerospace applications, military hardware, oil wells, and nuclear plants. They hold up well under continuous 450F (323C) temperatures with up to 600F (316C) limited use. Fire resistance rating is UL 94 V-0; it resists abrasion and long-term mechanical loads (see **Polyaryletherketone**).

It is used in different applications. An example was in the design of a low speed air motor for dental attachments. Star Dental of Lancaster, PA., required a material for the sliding vanes and bushings that would not require lubrication. Thus the time and expense of lubricating the motor between dental patients would be eliminated. To ensure the optimum power of the equipment, components are molded to exacting standards with dimensional tolerances of less than 0.0005 in. Victrex USA, Inc., (Greenville, SC 29615) used PEEK not only for its inherent lubricity, but also for its ability to withstand repeated sterilizations. Components must withstand being autoclaved at 121C (250F) to 135C (275F) or chemiclaved at 132C (270F). The PEEK durability was tested up to 1000 cycles adding that the absence of residual lubricating oil coating was found to facilitate the sterilization process.

Polyether, Chlorinated

This corrosion resistant plastic is extensively used in the manufacture of products and equipment for the chemical and processing industries. CPE has also found use in molding components for pumps and water meters, pump gears, bearing surfaces, and the like. This plastic resists both organic and inorganic agents at temperatures up to 125C (257F) or higher. It does not resist fuming nitric acid and fuming sulfuric acid. Its heat-insulating characteristics, dimensional stability, and outdoor exposure resistance are excellent. CPE has excellent weathering resistance. Creep resistance at elevated temperatures is also excellent. The material exhibits an elongation under 1000 psi of 4.5% after 5 hr at 280F and of 1.5% after 12 hr at 75F. In addition, the plastic has good impact strength, low moisture absorption, and high dimensional stability. It retains its properties at elevated temperatures and can be used at 100 to 125C (212 to 257F).

Polyetherimide

A key feature of PEI is its ability to maintain properties at elevated temperatures. For example, at 180C (356F) its tensile strength and flexural modulus are 41 and 2.067 MPa (6.000 and 300.000 psi). The strength and modulus of the glass-reinforced grades are higher. The modulus at 9×10^3 MPa (1.3×10^6 psi) with 30wt% of glass to over 80% retained at 180C (356F). PEI also has good creep resistance as indicated by its apparent modulus of 2,410 MPa (350,000 psi) after 1,000 h at 82C (180F) under an initial load of 35 MPa (5,000 psi).[1] Provides good/easy processability.

They are also characterized by excellent electrical properties that remain stable over a wide range of temperatures and frequencies, with inherent flame resistance and low smoke evolution. Its UL continuous-use listing is 170C (338F) and its heat-deflection temperature is 200C (392F) at 1,820 kPa (264 psi). It has a T_g of 215C (419F), a UL rating of 94 V-O at a thickness of 0.016 in. and of 5v at 0.075 in. without additives. PEI has a limited oxygen index of 47% (one of the highest among the engineering TPs). It has a high-volume resistivity of 6.7×10^{17} ohm/cm and a dielectric strength from 830V/mil at ¹⁄₁₆in. in air to greater than 6,500 V/m in submil film thicknesses. Its arc resistance exceeds 120 s meeting one of the UL electrical requirements for the sole support of "live" parts. Use includes auto headlamp reflectors replacing metals.

PEI resists a broad range of chemicals under varied conditions of stress and temperature. PEIs resistance to mineral acids is outstanding. It is attacked by such partially halogenated solvents as methylene chloride. trichloroethane, and strong acids. These amorphous engineering plastic are characterized by heat resistance, flame resistance, and UV resistance. Neat (unmodified) PEI is transparent although of amber brown color. Its resistance to UV radiation is good with a change in tensile strength after 1,000 h of xenon-arc exposure that is negligible. Resistance to gamma-ray radiation is also good, there being a strength loss of less than 6% after 500 megarads exposure to cobalt 60 at the rate of one Mrad/h. Hydrolytic stability tests show that more than 85% of PEIs tensile strength is retained after 10,000 h of immersion in boiling water. This material is suitable for short term or repeated steam exposure.

Polyethylene Naphthalate

PENs are polyester plastic that are penetrating different markets such as the market for stretch blow molded bottles for filling at 98C (208F). When compared to the very popular PETs processing with the more expensive PENs do not require the use of energy consuming air-cooling. They are competing in markets previously off limits to plastics. With an oxygen barrier 5.6 times better than PET, it is reported that they will give the necessary protection to beer and to extended shelf life of food and fruit juices. For hot filled and fruit juices, PEN can be used. Greater temperature resistance makes PEN more acceptable packaging beer, which is pasteurized in the container. For products where flavor is crucial, from beer to mineral water, acetaldehyde extractables tend to run only 20% as high as PET. For pharmaceuticals, a benefit is that it almost totally blocks UV light. Returnable/recycled bottles better resist caustic washing.

Polyethylene Terephthalate

PETs, in the family of polyester plastics, are available in engineering grades providing high performance mechanical and electrical properties. It can be made into oriented and crystallized articles that still possess excellent clarity. Outstanding dimensional stability can be obtained in PET film by controlling orientation and by heat setting during processing. Very few other materials offer such a range of processing and property variables. For packaging applications PET is used because it combines optimum processing, mechanical, and barrier properties.

PET is known for its clarity and toughness when it is used for the manufacture of oriented film or stretch-blown bottles. It is also a good barrier to gases, such as oxygen and carbon dioxide. The good oxygen barrier properties of PET allow for its use in carbonated beverages and many types of food containers. However PET barrier properties are deficient for packaging beer and certain foods that are highly sensitive to oxygen unless coinjected with suitable materials. PET can be reinforced with glass fibers to produce an injection molded product with high heat resistance and high stiffness. The resistance of PET to chemicals and solvents is greatly enhanced as the crystallinity of the polymer increases.

PET's broad range of properties make them ideal replacements in certain applications for such metals as die-cast aluminum or zinc; also in thermoset switches, relays, sensors, etc. Applications include packaging (particularly stretched injection blow molded beverage bottles and film), appliances, electrical/electronics, etc. PET finds applications in such diverse end uses as fibers for clothing, films, bottles, food containers, and engineering plastics for precision molded parts.[118-120] A wide range of applications is possible because of the excellent balance of properties PET possesses and because the degree of crystallinity and the level of orientation in the finished product can be controlled.

PET plastics are hygroscopic so require proper drying before processing. They can be extruded, blow molded, and thermoformed on conventional equipment if dried to a moisture content of less than 50 ppm. Recycling all types of PET materials is easily accomplished. Of the 2002 total USA 49.4 million units of PET beverage container market 57% contain carbonated soft drinks and 24% contain water.[485]

Polyethylene Terephthalate Glycol

The clear, amorphous, glycol-modified polyester PETG is polymerized from dimethyl ester (DMT) or terephthalic acid (PTA), and ethylene glycol. The addition of glycol prevents polymer crystallization, providing a broader process window than PET. PETG parts such as blow molded bottles have good clarity, toughness, and ESCR (environmental stress cracking resistance) performance, as well as good gas barrier properties. Major sheet markets include medical trays, rigid packaging, and point-of-purchase displays.

Polyhydroxybutyrate

During 1992 researchers passed what was called a crucial milestone in efforts to create farm crops that would make it possible to grow high-quality biodegradable plastics. Agricultural scientists at Michigan State University in East Lansing, Mich., and University in Harrisonburg, VA. used genetics to create an experimental plant that makes a plastic called polyhydroxybutyrate (PHB). It is much like PP except that it is biodegradable It is reported to be the first plant that has been genetically engineered to make something other than a protein. Britain's ICI previously made PHB using a soil bacteria acaligenes eutrophus that is being used in blow and injection molding. Researcher's at Michigan used three genes identified and cloned from the bacteria ICI used in 1987.

Polyimidazole

A variety of polymidazoles can be prepared by aromatic nucleolphilic displacement, from the reactions of bisphenol imidazoles with activated difluoro compounds. These plastics have good mechanical properties that make them suitable for use as films, moldings, and adhesives.

Polyimide

The first so-called high-heat-resistant TPs were the PIs a family of some of the most heat- and fire-resistant plastics known. They are available in both TPs and TSs. Moldings and laminates are generally based on TSs, though some are made from TPs. PIs are available as laminates and in various shapes, as molded parts, stock shapes, and plastics in powders and solutions. Porous PI parts are also available. Uses include critical engineering parts in aerospace, automotive and electronics components subject to high heat, and in corrosive environments. Parts include wire enamel, insulating varnish, and coated glass fabrics. The insulating varnish possesses good electrical properties in the –190 to 340C (–310 to 644F) temperature range. Generally, the compounds that are the most difficult to fabricate are also the ones that have the highest heat resistance.

They have a density of 1.41 to 1.43, tensile strength of 12,000 psi at 73F, and an elongation of 6.8% at that same temperature. They have a low coefficient of expansion. PIs retain a significant portion of their room temperature mechanical properties from –240 to 315C (–400 to + 600F) in air. The service temperature for the intermittent exposure of PIs can range from cryogenic to as high as 480C (900F). Their deformation under a 28 MPa (4.000 psi) load is less than 0.05% at room temperature for twenty-four hours. Glass-fiber reinforced PIs retain 70% of their flexural strength and modulus at 250C (480F). Creep is almost nonexistent, even at high temperatures.

These materials have good wear resistance and a low coefficient of friction, both of which are factors that can be further improved by including additives like PTFE. Self-lubricating parts containing graphite powders have flexural strengths above 69 MPa (10,000 psi.) Their electrical properties are also outstanding over wide temperature and humidity ranges. They are unaffected by exposure to dilute acids, aromatic and aliphatic hydrocarbons, esters, alcohols, hydraulic fluids, JP-4 fuel, and kerosene. They are, however, attacked by dilute alkalis and concentrated inorganic acids.

PIs show good radiation resistance, and retain useful properties after absorbing radiation doses as high as 6.000 megarads. Polyimide laminates curing conditions are 200 psi at 370C for 1 h. Laminates have shown 25% strength retention after 1000 h at 315C. The resins do lose considerable strength in air at service temperatures above 315C. Typical polyimide film properties include tensile strength, 24,000 psi; modulus, 415,000 psi; elongation, 65%.

It is difficult to process by conventional means. Parts are fabricated by techniques ranging from powder-metallurgy methods to modifications of conventional injection, transfer, compression, and extrusion that include ram instead of screw plastication (Chapter 3). Since PIs are essentially nonfusible and difficult to fabricate by conventional shaping processes. As an example DuPont with its Kapton has employed special processes, including a high temperature-pressure procedure similar to that used in powder metallurgy, to fabricate its PI into finished parts (called Vespel). This process is useful for producing parts for low friction, high temperature applications.

Polyimide Powder

Special PI powders with desirable melt flow behavior and properties are formed in reaction vessels, without grinding (NASA Langley Research Center, 1994). Crystalline PIs that have controlled molecular weights can be synthesized in a process that yields the PIs in powder form. They exhibit transparent crystallinity that gives rise to melt flow of a high degree at processing temperatures of about 300 to 350C (572 to 662F) that are slightly above their melt temperatures. They are commercially attractive for processes such as extrusion, injection and compression molding of complex shaped parts, adhesive bonds, and deposition onto reinforcing fibers for subsequent hot pressing into PI-matrix/fiber reinforced plastics.

Polyesterimide

These PEI plastics show good physical and electrical properties at high temperatures and a 20,000 h service life at 230C (446F). Their thermal-oxidative stabilities are described as being less than the best polyimides, but better than the aromatic polyesters.

Polyketone

PK are crystalline engineering TPs that provide high performing thermal, mechanical, chemical, and electrical properties. They are used in a variety of products for the electrical, automotive, aerospace, chemical, and oil industries. They compete for applications with ceramics, glass, metals, thermoset plastics, and heat-tolerant and chemical resistant engineering thermoplastics such as polysulfone, polyimide, polycarbonate, fluoropolymer, and some nylons. The family of PKs, also called polyaryletherketones (PAEKs), consists of polyetheretherketone (PEEK), polyetheretherketoneketone (PEEKK), polyetherketone (PEK), and polyetherketoneetherketoneketone (PEKEKK). They share similar molecular structures based upon repeating ether and ketone groups in various ratios.

Polyetheretherketone
With its flexibility, PEEK behaves like a true TP and has the ability to crystallize (25 to 50%). Its high glass transition temperature (T_g) and the high melting point (T_m), combined with high temperature chemical stability, rate this plastic in the most temperature resistant TPs. As with other crystallizing TPs, crystallinity can develop only at temperatures between T_m and T_g, a fact that must be taken into account for processing (extrusion, injection, etc.). PEEK retains good mechanical properties at high temperatures such as 200C (392F) for periods of time. They have a very low flammability and very low smoke and toxic gas emission. It is practically insoluble in any solvents and particularly resistant to hydrolysis by steam or high temperature pressurized water, absorbs little moisture, and has excellent resistance to nuclear radiation. As other crystallizing materials, it is resistant to environmental stress cracking.

Polyetheretherketoneketone
PEEKK provides high performance plastics that meet the growing requirement for thermal stability and mechanical strength in the electronics, automotive, and mechanical engineering industries. Their chemical bonds rank among the most stable ones in organic chemistry. The molecules are closely packed over wide areas, forming crystalline regions. This crystallinity with the chemical nature of PEEKK provides its exceptional performance. Its most important property has been its resistance to dimensional changes (softening) when exposed to high temperatures and also its resistant oxidation as it ages.

Polylactide

PLA is a biodegradable plastic. The first worldwide production facility for PLA opened by Cargill Dow LLC joint venture occurred at the end of 2001 in Blair, Nebraska. The plastic is made from lactic acid which is produced from cornstarch and other plant carbohydrates by bacterial fermentation. PLA shows good clarity, gloss, deadfold, twist retention, heat-sealability, and flavor and aroma barrier. After use, the material is fully compostable. Using material from a semi-works plant, Cargill Dow has already developed applications in fibers, thermoformed containers, cups, and packaging films. Their commercial uses include film for packaging, golf balls, and mini-CDs. Thermoformed trays and film for packaging fresh pasta and salads is already in place.

Polyorganophosphazene

PPZ is a plastic involving inorganic chains. In this case, atoms of nitrogen (N), and phosphorus (P) form the chain of a variety of organic side groups that can be attached to the phosphorus atom. The resulting high molecular weight chains are often flexible (low glass transition temperature, T_g) and thus are suitable as elastomers. Types with higher T_g and crystallizing types have good applications as coatings, fibers, and biomedical materials. PPZs are inherently fire resistant, offer good weatherability, and water and oil repellency.

Polyoxymethylene

POM is usually called acetal; also called polyacetal. See **Acetal**.

Polyparamethylstyrene

PPMS homopolymer is fairly similar to PS with a slightly higher glass transition temperature. It is a low-cost alternative for styrene in homopolymers and copolymers.

Polyperfluoroalkoxy

PPFA is a so-called fully fluorinated plastic which has properties quite close to those of PTFE while being a true TP processwise.

Polyphenylene Ether

PPE compounds are characterized by outstanding dimensional stability, low water absorption in the engineering TPs, broad temperature ranges, excellent mechanical and thermal properties from –46 to 121C (–50 to 250F), and excellent dielectric characteristics over a wide range of frequencies and temperatures. Several injection molded and extrusion grades are rated UL 94 V–1 or V-O including the glass fiber reinforced compounds. Because of their hydrolytic stability, both at room and elevated temperatures, blended parts in PPE can be repeatedly steam sterilized with no significant change in their properties. When exposed to aqueous environments their dimensional changes are low and predictable. PPEs resistance to acid, bases and detergents are excellent. However. it is attacked by many halogenated or aromatic hydrocarbons. Foamable grades have service temperature ratings of up to 96C (205F) in ¼ in. sections.

PPE products are used in different applications. Their unique compatibility with PS, particularly HIPS, results in a wide range of high temperature, tough, dimensionally stable products. They can be processed by conventional equipment that produces either solid or foam products.

Polyphenylene Oxide

PPOs have high glass transition temperature (T_g). Both transparent and opaque grades are available. They have good hydrolytic resistance, are soluble in chlorinated and aromatic hydrocarbons, and have good mechanical and electrical properties over a wide temperature range [–170 to 190C (–274 to 374F)]. They are not so thermally stable as polyimides or polybenzimidazoles. The material has a brittle-point of –170C. Representative properties of the PPO include heat deflection temperature, 192 to 194C (375 to 399F) at 264 psi; tensile strength at yield, 75 MPa (11,000 psi); tensile modulus, 0.03 MPa (3.8×10^5 psi); tensile elongation at break, 5 to 6%; and flexural strength at yield, 100 MPa (14,500 psi). The PPOs can be injection molded (343C/8,000 to 12,000 psi) or extruded (288C) on standard equipment, and can be machined like brass. Melting point (T_m) is 260C (500F).

Electrical properties are generally good and unaffected by moisture. Dielectric properties, in particular, are good and stable. They are classified as self-extinguishing and non-dripping. Hydrolytic stability is exceptionally high. it is also highly resistant to water, including hot water and steam. It can be repeatedly sterilized in steam autoclaves.

Cost and certain processing difficulties associated with a high melt viscosity originally led to the use of blends (polyalloys) with PS or HIPS resulting in a single T_g about 150C (302F) to blends from 100 to 135C (212 to 57F). These lower T_g blends are often referred to as modified PPO (MPPO). The mechanical properties of MPPO are generally good with high stiffness and low creep over a wide temperature range. Good toughness extends to low temperatures. Excellent dimensional stability is associated with the noncrystalline structure, a low coefficient of thermal expansion, and very low moisture absorption.

Polyphenylene Sulfide

PPS engineering plastic is characterized by its outstanding high-temperature stability, inherent flame resistance, broad range of chemical resistance even at high temperatures, below 200C (400F) has no known solvent, and are flame retardant without additives being rated at UL 94 V-O. The oxygen index of the neat resin is 44 with the indexes of the compounds ranging from 47 to 53. PPSs and compounds provide various combinations of high mechanical strength, impact resistance, and electrical insulation, with its high arc resistance and low arc tracking. The pigmented PPS compounds include several grades that are suitable to support current-carrying parts in electrical components. They are essentially transparent to microwave radiation. Crosslinked types are more crystalline than any of the sulfones that are generally classified as being more amorphous. They are quite stiff with a flexural modulus ranging from 11.7 × 10^3 to 17.2 MPa (1.7 × 10^6 to 2.5 × 10^6 psi). Their tensile strengths range from 69 to 172 MPa (10,000 to 25.000 psi). Their HDTs (heat distortion temperatures) are up to 275C (525F) at 1,820 kPa (264 psi).

Polyphosphazene

As a coating offers increased anti-icing effectiveness and durability than fluorocarbon and silicone elastomers. These icephobic coats can reduce the accumulation of ice on products such as rooftops, aircraft, radomes, antennas, ships, and power-transmission lines. The weight of such accumulations of ice has led to aircraft crashes, fallen power lines, etc. The icephobic coats reduce the adhesive force between ice and a surface. Polyphosphazene elastomers possess these desired properties, in addition have low glass transition temperature (T_g), good environmental stability, curability, and moderate cost.

Polyphthalamide

These PPA heat resistant, high performance plastics have been used successful in different applications such the auto engine block. BP Amoco reports that after seven years and 85,000 miles of actual vehicle use, a Dodge Neon 2.0 liter thermostat housing molded from BP's PPA (polyphthalamide) showed no measurable dimensional variations, no surface degradation, and no decline in the performance of the plastic. In 1994, BP model A-113 3 HS (a 33wt% glass-filled, heat-stabilized grade) replaced die-cast aluminum and competing plastics in this application because of the PPA's superior corrosion resistance, superior chemical resistance to long-term exposure to engine coolants at 135C (275F), lower moisture absorption, improved hydrolytic stability, higher thermal resistance, approximate 20% weight reduction, and overall cost savings. The thermostat housing was designed and developed by the Powertrain Division of LDM Technologies (formerly HPG), headquartered in Auburn Hills, Mich.[281]

Polysulfone

PSUs are a family of engineering heat resistant plastics have good electrical properties, excellent chemical resistance (resistance to acids, bases, detergents, oils), high heat deflection temperatures, outstanding dimensional stability, biologically inert, rigid, strong, and easily processed by conventional methods. They have useful properties in the -100 to 150C (212 to 302F) temperature range.

They are stable and self-extinguishing in their completely natural, unmodified NEAT form (Chapter 1). In most plastics these qualities must be obtained by using chemical modifiers. They are also heat resistant and maintain their properties in a range from -100 to over +150C (-150 to over +300F). These strong, rigid plastics remain transparent and slightly clouded amber in color at service temperatures as high as 200C (400F). PSUs are available in opaque colors and in mineral-filled and glass fiber (and other reinforced compounds) to provide higher strength, stiffness, and thermal stability. For example, reinforced carbon fiber PSU is used in human hip joints.

The tensile strengths of PSUs go up to 110 MPa (16,000 psi), its flexural modulus to more than 1.0×10^6 psi, and its HDT to up to 200C (400F). A high percentage of its physical, mechanical and electrical properties are maintained at elevated temperatures. For example, its flexural modulus remains above 0.3×10^6 psi at service temperatures as high as 160C (320F). Even after prolonged exposure to such temperatures, the plastics do not discolor or degrade. Its thermal stability and oxidation resistance are also excellent at service temperatures well above 150C (300F).

Creep, compared with that of other TPs, is very low at elevated temperatures and under certain continuous loads. For example, its creep at 99C (210F) is less than that of acetal or heat resistant ABS at room temperature. Hydrolytic stability of these materials makes them resistant to water absorption in aqueous acidic and alkaline environments. Their combination of hydrolytic stability and heat resistance results in their having exceptional resistance to boiling water and steam even under autoclave pressures and cyclic exposure to hot-to-cold and wet-to-dry, repetitions.

Heat aging increases its tensile strength, HDT, and modulus appreciably. However, prolonged heat aging for about a year or so decreases its toughness, tensile strength, and elongation. PSUs exhibit notch sensitivity and are attacked by ketones, esters, and aromatic hydrocarbons. The PSUs also have the drawback of absorbing UV rays that gives them poor weather resistance. Thus they are not recommended for outdoor service unless they contain UV stabilized or are protected with paint or plated. Use includes medical equipment, solar-heating applications and other performance applications where flame retardance, autoclavability and transparency are needed.[121]

Polyethersulfone

PES is recommended for load-bearing applications up to 182C (360F) for tens of thousands of hours at 200C (390F) without a significant loss of strength. Even without flame retardants it offers low flammability and it has little change in its dimensions of electrical of properties in the temperature range from 0 to 200C (32 to 390F). At room temperature they are tough, rigid, and strong with outstanding long-term load-bearing properties.

PES possesses good resistance to x-rays. beta rays, and gamma rays. Even though it does not have good resistance to outdoor weathering, with a carbon-black filler it is acceptable. Its chemical resistance can be improved by annealing at 200C (390F). It has good resistance to aqueous acids, bases, and most inorganic solutions. Most of the common sterilizing solutions and anesthetics can be used with PES safely (many cleaning and decreasing solvents are based on chlorinated and fluorinated hydrocarbons). Unless PES is heavily stressed, it can be cleaned by most of these solvents.

Compared with most TPs, PES has low flammability without flame-retardant additives and carries a UL 94 V–0 rating at a thickness of 0.017 in. with glass reinforcement. Its limiting oxygen index is in the range of 34 to 41. Its smoke and gas emissions are very low. UL temperature index is 200C (390F) for a PES compound that is 30wt% glass fiber. Its dimensional changes at 200C (390F) are negligible although small variations occur in its electrical performance from 0 to 200C (32 to 390F).

Polyphenyl Sulfone

PPSUs provide excellent toughness, hydrolytic stability, creep resistance, high heat deflection temperature [204C (399F)] at 1.82

MPa (264 psi)], good electrical properties, good environmental stress-crack resistance (relative to other amorphous plastics), and low flammability based on standard laboratory tests.

Polyphenylethersulfone

PPESUs different formulations include those with a glass transition temperature of 220C (428F). Generally properties are similar to the common polysulfone. Temperature resistance is higher and it is less sensitive to stress cracking and to oxidative attack.

Polyphthalamide

This crystalline aromatic nylon, combines the high strength and stiffness of nylon with the thermal stability of polyphenylene sulfide. Molding characteristics are similar to nylon 6/6, with similar or better chemical resistance, but its 24 h water absorption is only 0.2 versus 0.7% for nylon 6/6. A key behavior is high heat resistance.

Polysaccharide

Naturally occurring polymers consisting of simple sugars. Used in adhesives.

Polyterpene

TP obtained by the polymerization of turpentine in the presence of a catalysts. These plastics are used in the manufacture of adhesives, coatings, varnishes, and in food packaging. They are compatible with waxes, natural and synthetic rubbers, and PE.

Polythiophene

Melt processable plastic that is electrically conductive.

Polyurethane, Thermoplastic

PUR or PU are also called TPU (thermoplastic polyurethanes) can be either TPs or TSs. Extremely wide variations in form and physical or mechanical properties are available in solid to foam PURs. They exhibit an extraordinary range of toughness, flexibility, and abrasion resistance. Its grades can range in density from 16 kg/m^3 (½ lb/ft^3) in its cellular form to 1,120 kg/m^3 (70 lb/ft^3) in a solid form. PUR's hardness runs from soft elastomers to rigid, solid forms at 85 Shore D. High strength and good chemical and abrasion resistance, with superior resistance to ozone, oil, gasoline, and many solvents characterize them. The rigid foam type is widely used as an insulation material in buildings, appliances, and so on. The flexible foam is an excellent cushioning material for furniture, and the elastomeric type is used in solid tires, shock absorbers, and so on. They have outstanding flexural life, cut resistance, and abrasion resistance. Some formulations are as much as 20 times more resistant to abrasion than are metals.[123–125, 473]

T_g of the flexible foams is well below room temperature, and for rigid foams the T_g is higher than room temperature. The cells of a rigid foam are about the same size and uniformity as those of a flexible foam, but rigid foams usually consist of 90% of closed cells. For this reason their water absorption is low. Compressing the foam beyond its elastic limit will damage its cellular structure. Rigid foams are blown with either carbon dioxide or fluorocarbons, although a nondamaging ozone-blowing agent is now replacing the fluoros. The blowing agent used and density influence their thermal conductivity (Chapter 8).

They are manufactured by reacting a polyfunctional alcohol with an isocyanate in a simple blend-reaction operation. By the proper choice of the alcohol and the isocyanate, polyester or polyether urethanes can be made. Similarly, either TPs or TSs urethanes can be made by the proper choice of isocyanate. As an example, PURs based on toluene diisocyanate (TDI) continue to hold a large proportion of the market in the soft-foam sector. However, TDI was generally outstripped by methane diisocyanate (MDI), since the more flexible chemistry of these isocyanates as compared to TDI made a wider spectrum of applications possible. MDI offers a highly developed building-block system whose elements allow widely differing materials (soft, semirigid, rigid) to be tailored to specific requirements. PUR alternative name for polyurethane elastomer is polyurethane rubber.

Polyurethane Elastomer
This term covers a very wide range of PURs classified according to the method of manufacture. The main types are cast PUR elastomer, millable PUR elastomer. and reaction injection molding PUR elastomer.

Polyurethane Isoplast
Dow's isoplast thermoplastic PUR have a unique "live" nature that combines the ease of processing of low molecular weight plastics and the engineering properties of the higher molecular weight (or lower melt index) plastics. They have clarity, toughness without notch sensitivity, and dimensional stability. Due to their extremely high molecular weight, they resist chemical attack, creep, and fatigue at a

level at least equal to such workhorse crystalline plastics as nylon and acetal.

Isoplast have very low viscosity melts and can be molded with low injection pressures 3.5 to 14 MPa (500 to 2000 psi) even in large, difficult to fill parts or with high loadings of glass fiber. During cooling, the molecular weight will increase approximately tenfold. Compared to most other TPs isoplast require rigorous drying, moderate low shear conditions, and good moisture control.

Polyurethane Virtually Crosslinked
TPUs are in a unique physical state. It has the properties of a thermoset elastomer without being crosslinked. Strong intramolecular forces, such as hydrogen bonds, van der Waals, London forces, and intramolecular entanglement of chains all contribute to the virtually crosslinked state. This state, however, depends on temperature. On heating the action of these forces disappears, permitting the plastic to be processed by standard methods used for a thermoplastic. On cooling, these forces reappear. The intramolecular forces of TPUs can be temporarily destroyed by salvation that enables them to be used in adhesives and coatings. When the solvents are evaporated, the original properties of the TPUs are restored.

Thermoset plastic

These plastics, after final processing into products, are substantially infusible and insoluble. Examples of their properties are reviewed in Table 2.5.

Alkyd

Alkyds are used primarily in paints and compression molding applications. Molding powders find use in encapsulating electrical and electronics devices because of their high strength, excellent electrical properties, dimensional stability, heat resistance, and may be light-colored. Mineral and glass fiber materials are often used to further strengthen them.

Allyl

There are two major allyl plastics, diallyl phthalate (DAP) and diallyl isophthalate (see **Diallyl phthalate**). Both of these are widely used in fiber reinforced forms. The allyl plastics are usually compression or transfer molded performing well in automated equipment (Chapter 14). They retain their physical and electrical characteristics under prolonged exposure to severe environmental conditions. They have high heat and moisture resistance, excellent electrical performance, good chemical resistance, dimensional stability, and low creep. These plastics are used where they're environmental resistances are important.

Amino

The family of aminos include melamine and urea-formaldehydes (to be reviewed later in this section). Melamine formaldehydes (MFs) have excellent electrical properties, heat and moisture resistance, and abrasion resistance (good for dinnerware and buttons); in high-pressure laminates it is resistant to alkalies and detergents. They have been used as the plastic for counter tops. Urea-formaldehydes (UFs) have properties similar to melamines and have been used for wall switch plates, light-colored appliance hardware, buttons, toilet seats, and cosmetics containers. Unlike MFs they are translucent, giving them a brightness and depth of color somewhat similar to opal glass.

Chlorosulfonated Polyethylene Elastomer

CSPE have excellent combinations of properties that include total resistance to ozone; excellent resistance to abrasion, weather resistance even in light colors, heat, flame, oxidizing chemical, solvents, crack growth, and dielectric properties. Also provide low moisture absorption, resistance to oil similar to neoprene, low temperature flexibility is fair at –40C (–40F), low gas permeability for an elastomer; and good adhesion to substrates. Can be made into a wide range of colors. Use includes hoses, roll covers, tank liners, wire and cable covers, footware, and building products (flash, sealing, etc.).

Cross-Linked Polyethylene

XLPE (also called PEX) is PE that by chemical or irradiation treatment becomes a TS with significant improvements in properties such as strength, chemical, and outstanding heat resistance. XLPE can be produced by the addition of small amounts of organic peroxides (dicumyl, peroxide, etc.) that do not cause significant crosslinking before the plastic has acquired its final shape in processing. Process such as rotational molding is suited to this crosslinking method. Another method involves the irradiation of finished products in high-energy fields. It is used particularly for extruded-products, such as films (shrink-wrap film in particular), pipes, foams, and wire/cable insulation[626] (Chapter 8).

Table 2.5 Property guide for thermoset plastics

Property	Polyesters	Epoxies	Phenolics	Melamines	Silicones	Polyimides
Specific gravity color	1.10–1.45	1.10–1.4	1.30–1.86	1.40–1.48	1.30–1.34	1.42–1.90
Possibilities	Very good	Good	Limited	Very good	Good	——
By-products of cure	None	None	H_2O	H_2O	H_2O, RCOOH	H_2O
Molding pressures	0–high	0–high	Low–high	Medium–high	Low–high	Low–high
Molding temp., °F	<70–320	<70–330	270–320	270–360	280–360	330–660
Shrinkage, %	2–8	0.1–0.4	1–1.2	1–1.5	1–1.5	0.1–0.3
Tensile strength, 10^3 PSI	6–10	4–13	6–9	7–9	4–5	5–27
Elongation, %	5	2.6	1.5–2.0	——	——	<1–10
Modulus of elasticity tension, 10^3 PSI	3–6.5	4–6	4–5	7.5–10	——	1.9–28.5
Compressive strength, 10^{-3} PSI	13–36.5	15–21.5	12–15	40–45	9–15	4.7–40.0
Flexural strength 10^3 PSI	8.5–18.5	13–21	11–17	11–14	9–14	7.1–49.5
Impact strength (Izod)	0.2–4	0.2–1.0	0.25–0.40	0.24–0.40	0.25–6.0	0.25–0.8
Heat resistance °F (continuous) (°C)	250–500 (121–260)	250–500 (121–260)	160.250 (71–121)	210 (99)	>600 (315)	>600 (315)
Heat distortion, °F (°C)	140–400 (60–204)	115–550 (46–288)	165–260 (74–127)	298 (148)	>900 (482)	270–680 (132–360)
Water absorption, %, (24 hrs.)	0.15–0.60	0.08–0.15	0.03–0.04	0.3–0.5	0.1–0.5	0.11–0.60
Dielectric strength V per mil	200–420	400–500	360–400	300–400	200–500	250–725
Dielectric constant (60–10^6 CPS)	2.8–5.2	3.3–5.0	4.0–7.5	4.3–7.6	3.2–5.2	3.2–131.5
Dissipation (power factor 60–10^6 CPS)	0.003–.028	0.002–.050	0.01–.15	0.015–0.080	0.0008–0.01	0.0018–0.013
Arc resistance, sec.	125	45–120	Tracks	100–145	250–360	230
Burning rate	Slow to self-extinguishing	Slow to self-extinguishing	Very low	Self-extinguishing	None to slow	——

Effect of sunlight	Yellows	None	Darkens	Slight color change	None to slight	——
Effect of weak acids	None	None	None	None	None to slight	Resistant
Effect of strong acids	None to considerable	Attacked by some	Decomposed by oxid. acids, none to slight with regular org. acids	Decomposes	Slight	Slowly attacked–resistant
Effect of weak alkalis	None to slight	None	Slight to marked function of pH	None	None to slight	Slowly attacked
Effect of strong alkalis	Attacked	Slight	Decomposes	Attacked	Slight	Attacked
Effect of organic solvents	Attacked (ketones and chlorinated solvents)	Generally resistant	Attacked by some	None	Attacked by some	Very resistant
Machining qualities	Good	Good	Excellent	Fair	Fair to good	——
Major limitations	Cure shrinkage	Dermatitis, difficult to mold release	Colors limited	High cost	Very high cost	High cost
Major advantages	Ease of fabrication, clarity with flame retardancy, moderate dissipation (power) factor	Low shrinkage, excellent adhesion	Good general properties, low cost	Arc resistance, Scratch resistance, colorability	Heat resistance, low dissipation (power) factor	Heat resistance

Diallyl Phthalate

DAP and diallyl isophthalate (DAIP) are the principal thermosets in the allyl family with DAP predominantly used. DAPs' major use is in electrical connectors since they perform well in electrical circuits. Used also in RP laminates and molding compounds. In some applications DAPs are competitive with TS polyester compounds (BMC, etc.). They can offer longer shelf life [in the B-stage (Chapter 15)], less shrinkage during curing, somewhat better chemical or electrical properties, and higher heat resistance. In general they are more expensive.

They are molded at lower pressures and in faster molding cycles. With the triallyl cyanurate formulation, service temperature range can be as high as 260C (500F). Major advantages of all allyls over TS polyesters are freedom from styrene odor, low toxicity, low evaporation losses during fabricating evacuation cycles, no subsequent oozing or bleed-out, and long term retention of electrical-insulating performances.

Epoxy

Generally provide the highest performance of all TSs. Properties include very high strength in tension, compression, flexural loadings, very low shrinkages, hard, superior adhesion to other materials, etc. Can be cured chemically with or without heat. Used with glass cloth to make RP circuit boards, tooling surfaces for metals, RP castings, etc. Major use is as surface-coating materials where they combine toughness, flexibility, adhesion, and chemical resistance to a degree unmatched by almost any other plastic.

Epoxy Vinyl Ester

These plastics used in RPs (Chapter 15) can withstand many of the world's most aggressive chemical environments. Different formulated epoxies permit meeting exceptional corrosion resistance, different performance such as the ability to withstand exothermic stresses that are built up during curing, used in different temperature ranges.

Fluorosilicone Elastomer

The vulcanizates have a much-improved solvent resistance, especially to fuels and other hydrocarbons, compared with other silicone rubbers. They also retain their rather extreme low temperature flexibility and excellent high temperature resistance of silicones and fluoroplastics. Uses include seals and 0-rings for fuel pumps, aerospace applications, and underground use.

Melamine Formaldehyde

MFs are available in a wide variety of forms including molding powders, adhesives, laminating resins, and surface coatings. They are strengthened by the addition of reinforcing materials. Almost one-half of production go into adhesive applications. They are excellent plywood bonding agents that give water boil-resistant boards that meet extreme specifications for exterior weather uses. Other use includes furniture, clipboard, aircraft, boat building, and paperboard industries. Molding powders are used in plastic dishware and utensils and in electrical fixtures, appliances, and instruments. They provide heat resistance of 250F (121C), good electrical resistance, high moisture resistance, good dimensional stability, excellent mechanical strength and wear resistance, and easy to color.

Neoprene

Neoprene, or polychloroprene rubber (CR) was one of the very first synthetic rubbers produced. It was a material of choice for exterior applications such as profiles used in vehicles, building seals, and cables. Many more marketable products have benefited from this plastic. Except for SBR and IR, neoprene (CR) elastomers are perhaps the most rubberlike of all materials, particularly with regard to its dynamic response (Table 2.6). CRs are a family of elastomers with a property profile that approaches that of NRs (natural rubbers) but has better resistance to oils, ozone, oxidation, and flame. CRs age better and do not soften up on exposure to heat, although their high-temperature tensile strength may be lower than that of NRs. They are suitable for service at 250C (480F).

Neoprenes are resistant to oils and greases. Like NR, they can be used to make soft, relatively high strength compounds. One important difference is that, in addition to neoprene's being more costly by the pound than NR, its density is about 25% greater. CRs also do not have the low temperature flexibility of NR, which detracts from their use in low temperature shock or impact applications.

Phenol-Formaldehyde

PFs (phenolics) have been the low-cost workhorse since 1909 of the electrical industry. They have low creep, excellent dimensional stability, good water and chemical resistance, heat resistant, good weatherability, and have properties that are somewhat inferior to those of the more expensive TSs. Molded black or brown opaque handles for cookware

Table 2.6 Elastomer names

ASTM designation	Common or trade name	Chemical designation
IR	Synthetic natural rubber	Synthetic polyisoprene
IIR	Butyl, Chloro-butyl	Isobutylene-isoprene
ABR	Acrylic	Polyacrylate
AU	Urethane (UR)	Polyurethane (polyester)
EU	Urethane (UR)	Polyurethane (polyether)
BR	CBR, PBd	Polybutadiene
CO	Hydrin (CO, ECO)	Polyepichlorohydrin
CR	Neoprene	Chloroprene
CSM	Hypalon (HYP)	Chlorosulfonyl polyethylene
EPM	EP elastomer	Ethylene propylene copolymer
EPDM	EP elastomer	Ethylene propylene terpolymer
ET	Thiokol A	Ethylene polysulfide
EOT	Thiokol B	Ethylene ether polysulfide
EPM	Viton, Fluorel, Kel-F	Fluorinated hydrocarbon
NBR	Buna N, Nitrile	Butadiene-acrylonitrile
SBR	GR-S, Buna S	Styrene-butadiene
Si	Silicone	Organopolysiloxane
FVSi	Silastic LS	Fluorosilicone
—	Plaskon CPE	Chlorinated polyethylene
NR	Natural rubber	Natural polyisoprene

have been familiar applications. Also used as a caramel colored impregnating plastic for wood or cloth laminates, and (with reinforcement) for brake linings and many under-the-hood automotive electricals.

Phenolics are formulated with one- or two-stage curing systems. In general, one-stage plastics are slightly more critical to process. They have a time to temperature to viscosity behavior. Principally compression, transfer, and injection molding can process them. There are phenolics when processed that release water and others that do not release water. As is typical of many TSs, they are postcured to obtain maximum performance.

Polybenzimidazole

PBIs show via TGA test[3] that their thermal breakdown temperatures are as high as 600C (1110F) in nitrogen, but their thermal resistance is reduced to about 300C (572F) in air. Most are insoluble in all but exotic solvents, and show excellent resistance to oils, acids, and alkalies. They show useful stress and modulus properties in –253 to +650C (–389 to 1220F) temperature range (for at least short periods of time). Some have also been made that are more soluble and fusible. These plastics have high mechanical and physical strength properties including a high compression strength. PBI can bear loads for short periods at temperatures up to 650C (1,220F). They have low coefficient both of friction and of thermal expansion (0.000013 in/in/F).

PBIs have no known melting point. Its has a glass transition temperature (T_g) of 427C (800F). They have ultrahigh heat distortion temperatures of 435C (815F), retards flame, and will not burn in air. The material can withstand steady temperatures up to 427C (800F) and short bursts up to 760C (1,400F). The material resist steam at 343C (650F) and 15 MPa (2,200 psi) pressure. When exposed to saturated steam PBI absorbs only 0.4% moisture. It resists a wide range of chemicals including harsh ones.

They are fabricated by sintering under high pressures. The low molecular weight PBIs flow better than its high molecular weight (HMW) counterpart. However. HMW PBI outgases less during processing, making it more suitable to mold large products. They are generally infusible after curing and must be converted as prepolymers into useful forms prior to the final cures. The phenol further complicates fabrication by water side-products emitted during cures.

Polybenzobisoxazole

PBZs are a family of high performance liquid crystalline, rigid rod structure plastic compositions that are characterized by a unique combination of high molecular weight and concentration resulting in high tensile strength and stiffness, as well as resistance to moisture, heat, and UV exposure. Use includes structural composites for light-weight aircraft, military transportation, industrial products, and sporting goods.

Polybutadiene

General-purpose BR are more resilient than NRs. They were the elastomers that made the modern solid golf balls possible. They are superior to NRs in its low temperature flexibility and in having less dynamic heat buildup. However it lacks NR's toughness, durability, and cut-growth resistance. BRs can be used as blends in NR, SBR, and other materials to improve their low temperature flexing, but at a higher cost. It sacrifices key properties such as tensile strength, tear resistance, and general durability.

Polychloroprene

See **Neoprene.**

Polydicyclopentadiene

PDCPD is a highly crosslinked polyolefin. It is processed by reaction injection molding at low temperatures and pressures (Chapter 12). Its low viscosity and potential to extend gel times to a matter of minutes allow the production of very large parts. Parts are fabricated with high gloss (automotive Class A) and relatively high mechanical properties. This 1.03 specific gravity plastic (unreinforced) is very rigid having a flexural modulus in the order of 1895 MPa (275,000 psi); reinforcing with glass fiber doubles the value. Notched Izod impact strength is in the 5 to 6 ft-lb/in (267 to 320 HJ/m) and remains above 3 ft-lb/in (160 HJ/m) to at least -40C (-40F). The high gloss surface is quite hard (Rockwell R113 to 114) and, unlike TP polyolefins, exhibits excellent paint adhesion. Heat distortion temperature at 264 psi is 104 to 116C (220 to 240F). Like other polyolefins it is resistant to a wide range of chemicals, including alcohols, acids, and bases, It is attacked by some organic solvents, particularly chlorinated and aromatic hydrocarbons. Available is a corrosion resistant formulation designed for long term use with strong acids or bases.

Polyester, Thermoset

The two major groups are the TSs which are usually typified by a crosslinked structure and the TPs which are highly crystalline with comparatively high melting points (previously reviewed). TP polyesters are often called saturated polyesters to distinguish them from unsaturated polyesters that are the TSs. The unsaturated polyesters are supplied as solutions in a vinyl monomer with styrene. Before application an initiator and a promoter are added, usually together with extra vinyl monomer. A copolymerization is thereby initiated. Since the 1940s the major use for these plastics is in reinforced laminates, moldings, or coatings. There have been several instances in which polyesters have been separated into three groups and called polyesters, diallyl phthalates, and alkyds. This review only concerns TS polyesters; others have been reviewed.

They have an excellent balance of properties, a room-temperature cure, and is a major plastic used to fabricate glass-fiber reinforced products such as automobile parts, aircraft parts, and boats; used also with other type reinforcing agents. Commodity types have moderate weatherability, high molding shrinkages with wavy surfaces and warpage. Low-profile (styrene, etc.) additives reduce shrinkage and surface waviness to almost nil. This has led to major growth in the use of bulk molding compounds (BMC) and sheet molding compounds (SMC) (Chapter 15).

Processing with the styrene monomer requires that precautions have to be taken to ensure the proper removal and handling of this toxic material. Legal limits in the workplace have been set up by regulations. Other monomers used include diallyl phthlate (DAP), para-methylstyrene (PMS), vinyl acetate (VA), vinyl toluene (VT), adding paraffin wax, and styrene suppressant additive. Suppliers and fabricators continue to target in the reduction of styrene monomer quickly, effectively, and economically. A wide variation in properties can be obtained by changes in polyester formulation.

Polyester, Water-Soluble
These polyesters (WSPs) have increased use significantly in the surface coatings industry. Their largest use is in surface coating as pigmented electrodeposition and conventional dipping primers. Other applications include sprayed primer surfaces, semi-gloss trade-sales paints, coil-coating vehicles, and enamels applied by dip, flow-coat, electro-deposition, and spray methods. They provide ease of application, ease of cleanup, freedom from toxicity, and freedom from flammability when compared to conventional solvent based paint. They can be utilized as hydrophilic plastics in paper coating and textile coating. In most surface coatings, clear or pigmented solutions are converted to water-in-soluble coatings by condensation or oxidative polymerization.

Compressive strengths approaching those of concrete are obtainable at 50 to 60% water. Tensile and flexural strengths correspond to at least those of wood and related materials of construction. Impact strengths, even at 60% water, are significantly improved over plaster. When substituted for plaster, these polyesters provide significant reduced breakage of decorative art objects during shipping and improved durability for the consumer.

Polyimidazopyrrolone

These plastics, also known as pyrrones, are experimental materials prepared from aromatic dianhydrides and aromatic tetraamines. The polymer syntheses provide soluble prepolymers that are converted to the pyrrone structures by thermal or chemical dehydration. The precursors can be used to cast films or coatings, or can be molded under very high pressures into filled or unfilled forms. The pyrrones combine some of the best properties of the polybenzimidazoles and polyimides. The pyrrone films are exceptionally radiation resistant and retain their strength properties after 10,000 megarads of 1-MeV electrons.

Polyisobutylene Butyl

PIB is different from most common rubbers/elastomers by having very low gas permeability and very high damping/energy absorption properties. They have good weathering, ozone, heat aging resistance, capable of strain-crystallization, and can have good mechanical resistance. Resistance to oils and fuels is not good. If isobutylene is copolymerized with a small fraction of isoprene (1 to 2wt%), the isoprene unsaturations can be used for conventional vulcanization. Such an isobutylene-isoprene copolymer is referred to as butyl rubber (IIR). A major limitation of butyl rubber is its poor compatibility with other common rubbers/elastomers and generally results in low adhesion properties. Partial chlorination or bromination brings a marked improvement and also allows faster cure. Such modified butyl rubbers are referred to as chlorobutyl rubber, bromobutyl rubber, or halobutyl rubber.

Polyisoprene

IRs (sometimes abbreviated PI) are chemistry's nearest approach to synthesizing rubber equal to natural rubber (NR/thermoset). The synthetic rubber that comes closest to duplicating the chemical composition of natural rubber is this synthetic polyisoprene. One significant disadvantage of IRs are lack of green strength, which is to say during the time period during processing, prior to curing. An IR can be used interchangeably with NR in all but the most demanding products. IRs share with NRs the properties of good uncured tack, high-unreinforced strength, good abrasion resistance, and characteristics that provide good performance in dynamic applications. However, because of having some inherent impurities, NR is somewhat better overall. Its low hysteresis and high tensile strength distinguish NR. However solvents, gasoline, and ozone readily attack it. Its tensile strength is in the range of 24 to 31 MPa (3,500 to 4,500 psi) and its elongation is 550 to 650%. Applications are about the same as for NR.

Natural Rubber and Other Elastomer

Extensive data on properties and compounding (Figure 2.5) are available regarding natural rubber (NR) and other elastomers.

Polynorbornene

PNB has a glass transition temperature of 35C (95F). This plastic can easily be plasticized with large amounts of oil, subsequently vulcanized into an elastomer with a low service temperature of –65C (–85F). The damping properties of the elastomer can be adjusted to meet different performance requirements.

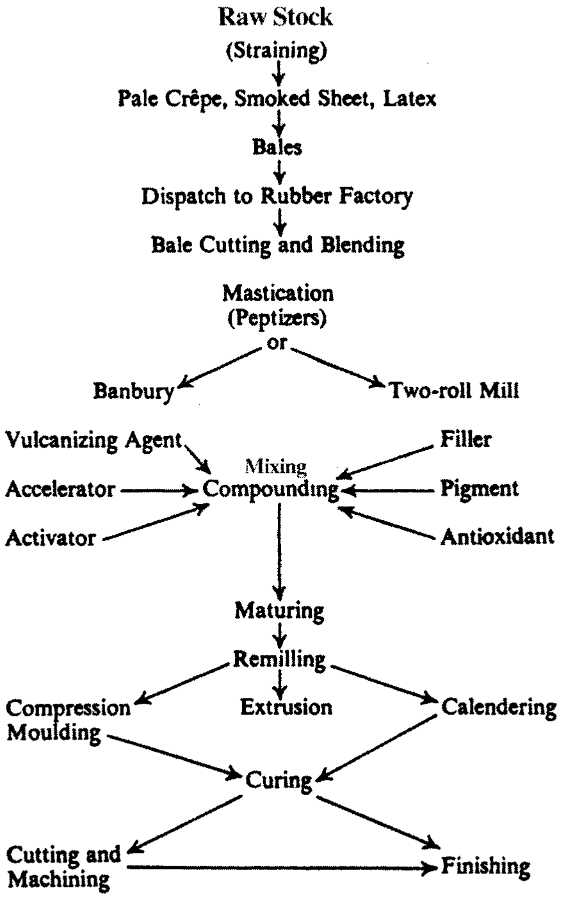

Raw Stock
(Straining)
Pale Crêpe, Smoked Sheet, Latex
Bales
Dispatch to Rubber Factory
Bale Cutting and Blending
Mastication
(Peptizers)
or
Banbury
Two-roll Mill
Vulcanizing Agent
Accelerator
Activator
Mixing
Compounding
Filler
Pigment
Antioxidant
Maturing
Remilling
Compression Moulding
Extrusion
Calendering
Curing
Cutting and Machining
Finishing

Figure 2.5 Basic compounding of natural rubber

Polysulfide

SRs contain sulfur and carbon linkages that are thermoset elastomers (TSEs). They have outstanding resistance to oils, greases, and solvents but have an unpleasant odor. Their resiliency is poor and their heat resistance is only fair. The abrasion resistance of polysulfides is half that of NR and its tensile strength runs only from 8.3 to 9.7 MPa (1,200 to 1,400 psi). However these values are still retained even after extended immersion in oil. Their increased sulfur content improves their solvent and oil resistance but reduces their permeability to gases.

Polyurethane, Thermoset

TPUs have durometers that range from soft cushion to glass hard with superior wear resistance. Use includes skateboard wheels, solid tires, floor coatings, marine finishes, etc. A major use for soft-foam is automotive bumpers; another is upholstery. Basically property improvements are made with added fibers and fillers in reaction molded products to improve cut strength resistance, stiffer moduli, reduce waviness caused by heat and weathering, etc. See **Polyurethane, Thermoplastic** for more details.

Rubber, Natural

Adding to what has been reviewed with **Polyisoprene** NR is important worldwide providing materials that inherently have useful and required properties with fabricating techniques that the synthetic plastic industry inherited. In fact the NR processes, principally compression molding and vulcanization, were expanded in order to process certain elastomeric plastics. Even though the major-marketed products are tires, NR is used in many other products (seals, gaskets, etc.). NR's consumption is not expected to rise much above the current 40wt% when compared to elastomeric plastics, and some sources are projecting a decline. Worldwide consumption of NR is estimated to be about 7 million metric tons in 2003.

The productivity of NR trees is slowly increasing, primarily through the maturing of higher-yielding clones, the use of chemical stimulants and the improved cultivation of seedlings. Hevea brasiliensis trees are now being tapped six years after planting versus seven years just a decade ago. Increased replanting may be necessary to avoid future natural rubber shortages. Asia continues to dominate the world averaging 94wt% of total production. [Over a century ago when the rubber industry started, the only source worldwide was from Brazil. Interesting history on how their trees where exported illegally.] However, there has been a significant shift among the major producing countries. Malaysia, which accounted for 32wt% of world production a decade ago, now produces less than 13% and continues to shift emphasis to other crops and nonagricultural investments. Thailand has become the world's largest producer of natural rubber, with a growth rate averaging 8% yearly since 1988. Indonesia also has potential for long-term growth because of the availability of land and labor. Other Asian countries (India and China) have also steadily increased their share of world production.

Rubber Latex, Natural

NR latex contains about 35wt% natural rubber hydrocarbon as particles that are about 1 μm in diameter and about 5% non-rubber components consisting of protein, lipid, sugar, and salt. Most latex is coagulated by the addition of acetic or formic acid to produce solid material. Some latex is used as the latex itself after concentration to about 60% rubber content by centrifugation or creaming. The stability of concentrated latex is preserved by the addition of about 1.5% ammonia. This releases the fatty acids from the lipids that stabilize the latex after the protein has broken down by natural microbiological attack. Use continues in commercial and industrial markets.

Silicone

Silicones is an alternate name for polyorganosiloxanes, being more frequently used when a plastic of this type is used as the basis of useful commercial products. They are a class of engineering plastics that are a semiorganic high molecular weight polymer ranging in physical form from rigid to flexible plastics. They have excellent heat resistance up to 260C (500F), chemical resistance, good electricals, etc. and a high cost. Just with glass fiber-silicone reinforced plastics, retention of mechanical and electrical properties up to 316C (600F) for relatively long time periods are obtained. RPs can be made by vacuum bag to higher pressure molding techniques (Chapter 15). Cure is generally at temperatures in excess of 150C (300F), depending on particular thermoset silicone used.

Silicone Elastomer

Silicone elastomers (Q), also called silicone rubbers, have a temperature range –51 to +316C (–70 to + 600F) that generally has little loss of properties. The unvulcanized polymer (dimethylsilicone gum) is usually crosslinked to a useful elastomer by heating with organic peroxide such as benzoyl peroxide or 2,4-dichlorobenzoyl peroxide. Different formulations are available. Special low molecular weight plastics with reactive end groups are room temperature vulcanized (RTV) silicone elastomers. RTVs are two-component liquids that are important to the plastics and other industries. This system combines the advantages of simple and rapid processing, analogous to that for TP elastomers, with those of an elastomer that ran be chemically crosslinked, and can be used over a wide (low to high) temperature range. The high reactivity allows injection molding with contact times as short as a few seconds, enabling one to produce small elastomer components in large numbers. Flexible molds for casting, etc. can quickly and easily be produced, and many other applications exist for RTVs. Despite their relatively high cost, they cost little to process, making them economically viable.[126]

Silicone elastomer vulcanizates have relatively poor mechanical properties compared to other elastomers and plastics [as an example tensile strength of 600 to 1,350 psi (4 to 9 MPa)]. However these properties are retained over a very wide temperature range. Typically, they have a useful life of about two years at 150C (300F) and retain their flexibility to about -50C (-60F) or lower. They retain excellent electrical properties under extremes of temperature and moisture, but have poor abrasion resistance. They swell moderately in oils, fuels, and in many solvents, although the fluorosilicones are much better in this respect. Copolymers are used to provide better compression set resistance, better low temperature properties, and improved solvent resistance.

Styrene-Butadiene Elastomer

SBRs, emerged as high volume substitute for NR during World War II because of their suitability for use in tires, belts, hoses, rubber floor tiles, and the like. Tensile strength after compounding it with carbon black and vulcanizing it is 17 to 24 MPa (2,500 to 3,500 psi), which is less than NR's, but it has an elongation of 500 to 600%. In abrasion and skid resistance they are superior to NR and have better resistance to solvents and weathering. They are used in applications where it has replaced NR, even though they do not have NR's overall versatility, because it meets product performance requirements and has a cost advantage over NR. For most uses SBRs must be reinforced to have acceptable strength, tear resistance, and general durability. It is significantly less resilient than NR, so it has higher heat buildup upon flexing. It also lacks NR's green strength and tack.

Urea-Formaldehyde

UF compounds are in the amino family of plastics. They are available in a wide range of colors, from translucent colorless and white through to a lustrous black. Unlike the limited colored phenolic (melamine formaldehydes) compounds, the molded UFs can be made with a considerable degree of translucency, giving them a brightness and depth of color somewhat similar to, although better, than opal glass. They are not affected by heat within their range of operating temperatures from -21C (-70F) to 80C (175F), but higher temperatures over prolonged periods will cause fading and eventual blistering. These self-extinguishing, odorless, and tasteless materials char at about 200C (395F).

Within their temperature limitations, UFs have good electrical properties. They have high dielectric strength, high arc resistance, no tendency to track after arcing, and a low order power factor. Their electrical properties are not greatly influenced by high humidity, and they resist static electricity buildup. Under dry conditions, UF moldings are remarkable resistant to corrosive fumes and have no effect on organic solvents in terms of absorption, swelling, or changes in appearance. However their water absorption is relatively high. UF intermediate water soluble products are starting materials for the production of adhesives, surface coatings, paper conditioners, and other such special items that require heat and catalysts for their final curing. They are used to bond laminated sheets, sometimes only on the surface, for color effects.

Elastomer

Elastomers is a rubber-like material (natural or synthetic) that is generally identified as a material which at room temperature stretches under low stress to at least twice its length and snaps back to approximately its original length on release of the stress (pull) within a specified time period. This term is often used interchangeably with the term rubber. Although rubber originally meant a thermoset elastomeric material obtained from a rubber tree, it identifies any TS elastomer (TSE) or TP elastomer (TPE) material.[84-89]. The term elastomer and rubber are usually used interchangeably. They represent a major and important segment in the plastic industry (Table 2.6). New elastomers are always being developed to meet new industry requirements. Information on TP and TS elastomers has been included in the sections reviewed. This section extends their technical information.

Thermoplastic polyolefin elastomers (TPOs)
TPOs are basically two-component elastomer systems consisting of an elastomer finely dispersed in a thermoplastic polyolefin (such as polypropylene). The thermoplastic polyolefin is the major component. Thermoplastic elastomers (TPEs) include TPOs, TPVs (thermoplastic vulcanizates), etc. Properties of TPOs depend upon the types and amounts of polymers used, the method by which they are combined, and the use of additives such as oils, fillers, antioxidants, and colors. Blends and reactor-made products compete primarily with other TPEs and metals. There are vulcanizates (TPVs) that have higher elastomeric properties. They compete primarily with TS elastomers.

Vulcanization is a method for producing a material with good elastomeric properties (such as NR) that involves the formation of chemical crosslinks between high molecular weight linear molecules. The starting polymer (such as raw NR) must be of the noncrystallizing type and its glass transition temperature (T_g) must be well below room temperature to ensure a rubbery behavior.

Many different mixtures using two or more polymers are used with many containing proprietary treatments. As an example there are TPVs and melt-processable rubbers (MPRs). TPVs are essentially a fine dispersion of highly vulcanized rubber in a continuous phase of a polyolefin.[622] Its crosslinking gives them high tensile strength, high elongation, resistance to compression and tension set, oil resistance, resistance to flex fatigue, and maximum service temperature of 135C (275F).

As explained in the previous sections of this chapter, elastomers are used to fabricate many different products to meet many different requirements (Tables 2.7 and 2.8). Practical all fabricating processes are used (such as extrusion, injection molding, blow molding, compression molding, casting, and encapsulation) are used.

Table 2.7 Elastomers cost to performance guide

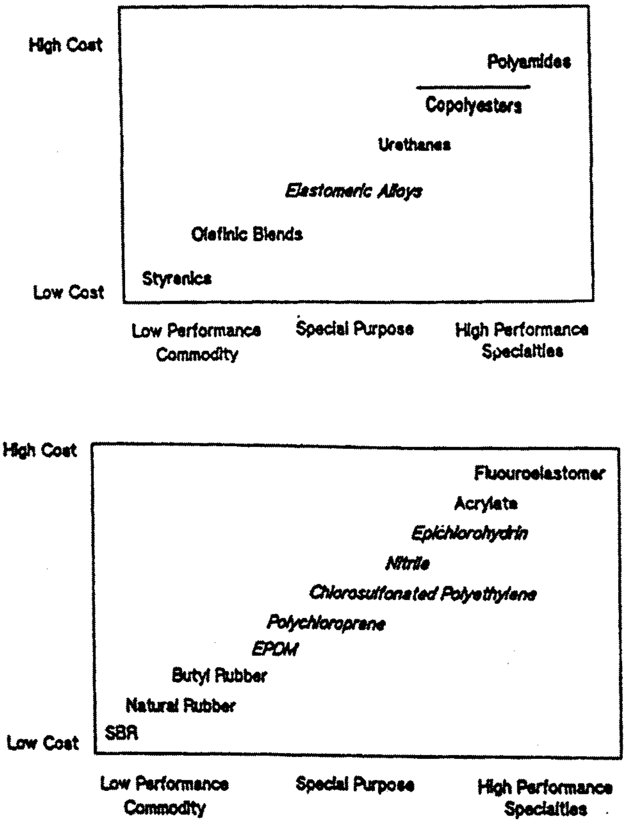

High Cost
Polyamides
Copolyesters
Urethanes
Elastomeric Alloys
Olefinic Blends
Styrenics
Low Cost
Low Performance Commodity
Special Purpose
High Performance Specialties
High Cost
Fluouroelastomer
Acrylate
Epichlorohydrin
Nitrile
Chlorosulfonated Polyethylene
Polychloroprene
EPDM
Butyl Rubber
Natural Rubber
SBR
Low Cost
Low Performance Commodity
Special Purpose
High Performance Specialties

Table 2.8 Guide to elastomer performances (where E = Excellent, G = Good, F = Fair, and P = Poor)

	Natural rubber	Isoprene rubber	Styrene-butadiene rubber	Butadiene rubber	Butyl rubber	Ethylene-propylene	Chloroprene rubber	Nitrile rubber	Polyurethane	Silicone	Fluorocarbon
Abbreviation(s)	NR	IR	SBR	BR	IIR	EPM, EPDM	CR	NBR	AU, EU	Q	FKM
Density, Mg/m^3	0.92	0.92	0.94	0.93	0.92	0.86	1.23	1.00	1.05	0.98-1.6	1.85
Glass transition temp., °C	−70	−70	−60	−105	−65	−58	−49	−24	−50	−120	−22
Temperature serviceability, °C											
lower limit	−55	−55	−45	−70	−50	−40	−35	−20	−50	−60	−20
upper limit, continuous	+70	+70	+70	+70	+100	+125	+100	+100	+70	+200	+200
intermittent	+100	+100	+100	+100	+125	+150	+125	+125	+100	+250	+250
Physical properties											
Hardness rang, IRHD	30–100	35–100	40–100	45–90	35–85	30–90	35–95	40–100	50–100	40–90	50–95
Tensile strength, MPa											
gum	24	21	3	3	10	3	17	4	35	7	17
reinforced	28	24	24	17	17	21	21	21	—	10	17
Resilience	E	E	G	E	P	G	G	P–F	F	F	F
Resistance to:											
tear	E	G-E	G	F	G	F	F	P–F	E	P	F
abrasion	E	E	E	E	F	F	E	F	E	F	G
compression set	G	G	G	G	F	G	G	G	G	G	G
creep/stress relaxation	E	E	G	G	F	F	F	F	F	F–G	G
gas permeation	F	F	F	F	E	G	G	G–F	G	P–F	E
Electrical resistivity	E	E	E	E	E	E	F	F	G	E	G
Environmental resistance to:											
heat	F	F	F	F	G–E	E	G	G	F	E	E
oxidation	F	F	F	F	G	E	G	G	G	E	E
ozone	P	P	P	P	G	E	G	P	E	E	E
flame	P	P	P	P	P	P	F	P	P	F	F
water	G	G	G	G	E	E	F	F–G	F	G	E
dilute acids	G	G	G	G	G	E	G	G	F	F	E
concentrated acids	F–G	F–G	F–G	F–G	F–G	G	G	F–G	P	F	

TPOs allow easy recycling of production waste and final products made of TPOs. Studies have shown that products can be manufactured from recycled TPOs without significant loss of performance. This can be seen as a big advantage compared with traditional rubber, which is relatively difficult to recycle and usually leads to inferior products. The disposal of used rubber products has become an ecological problem in the developed countries.

Reinforced plastic

RPs that combine two different materials (plastic matrix and reinforcement) are a separate major and important segment in the plastic industry. They are also called plastic composites and composites. There are also self-reinforcing plastics such as liquid crystal polymers (Chapter 1) and others.[301] It is a fact that RPs have not come near to realizing their great potential in a multitude of applications usually due to cost limitations that particularly involves the use of expensive fiber reinforcements (carbon, graphite, silica, etc.).[1] Information on thermoplastic and thermoset plastic RPs are reviewed in Chapter 15.

Recycled plastic

They include fabricating scrap, pre-consumer, and post-consumer plastics. In USA annually about 5¼ billion pounds are recycled with at present total recycling capacity at 7⅛ billion pounds.[75] Different systems are used for different materials and products based on thickness, degree of hardness, economics, etc. They include mechanical granulators, energy recovery systems (energy thermal reclamation), chemical recycling systems, and others. Granulators are predominantly used. There are different sizes and types of granulators used that process thin to thick plastics; flexible, soft, or hard plastics; unreinforced to reinforced; and so on. If large and thick plastic is to be granulated, two or more granulators are used to gradually reduce their size so that the minimum damage will occur to the plastic.

Recognize that a viable economic approach to recycling is by thermal incineration reclamation of electrical energy. Since there is unlimited raw material sources (vegetation, etc.) to produce plastics, the incineration approach can eliminate the problems associated with reusing recycled plastics.[3, 211]

When plastics are granulated the probability is its processability and performance when reprocessed into any product is insignificantly or significantly reduced. Thus it is important to evaluate what the properties of the recycled material provides. The size reduction and uniformity exerts a substantial influence on the quality/properties of the recycled plastics. When recycled plastics is nonuniform in size its processing with or without virgin plastics is subject to operating in a larger fabricating process window (Chapter 3).

Overheating is the major cause of damage to the plastic during the cutting action of the granulator. For heat sensitive plastics to eliminate any heat damage cryogenic granulating is used. A granulator that handles soft plastics will not work well when granulating hard plastic. One that handles thin plastic is not the proper type to handle thick plastics size and shape (bottles, solid handles, etc.). As an example two or more different performing granulators may be required to process thick material to ensure that overheating is minimized; a cascading action occurs by granulating the thick scrap and the next granulator further reduces the output from the first granulator.

Profitable business opportunities are gradually developing to produce many different products from recycled plastics such as boat docks, railroad ties, park benches, detergent bottles, office equipment, highway barriers, wastebaskets, pallet strapping, tool boxes, fast food trays, wetland walkways, signs, hampers, carpeting, irrigation pipes, paint cans, and many others.[78, 127–131, 425]

Plastic selection

Recognize that you have to be careful if selection is only made to compare plastic with other conventional materials (metal, wood, glass, etc.) on a straight property-for-property or a straight cost-for-cost basis. This approach is justified as an initial step but what is required is to include the cost of handling and processing plastics. A more expensive plastic may cost less to process, may provide a more desirable finish without secondary operations (Chapter 18), and so on.

About all one can be certain of is the fact that the technology of plastics has become so sophisticated that plastics are virtually the most versatile group of materials available to industry today. It has been interesting to note too how fast such sophistication has taken place. Almost a century ago, the rule of thumb was that TSs could not go much over 200C (392F) in service and TPs could not go over 55C (131F). In the mean time many new plastics have been developed such as the TP polyimides which will retain properties at temperatures up to 400C (750F).[132] And the aerospace industry has a group of materials known as ablative plastics (based on reinforced phenolics) that can take over 1100C (2000F) for short periods of time (less than an s). In the past it was generally accepted that plastics could not compete with other materials as load-bearing elements. But that was before engineering designs were properly applied; plastic structures were built such as aircraft to boat to bridge to spacecraft products.[248, 465]

The plastics material properties information and data presented in this chapter provide comparative guides. As reviewed in Chapter 1 plastics can be modified to meet all kinds of properties, performances, and processes by compounding, alloying, etc. Figure 2.6 provides a simplified summary in a pie section representing the properties of plastics. Literally each of the plastics can be modified to almost exist in any position within the pie section.

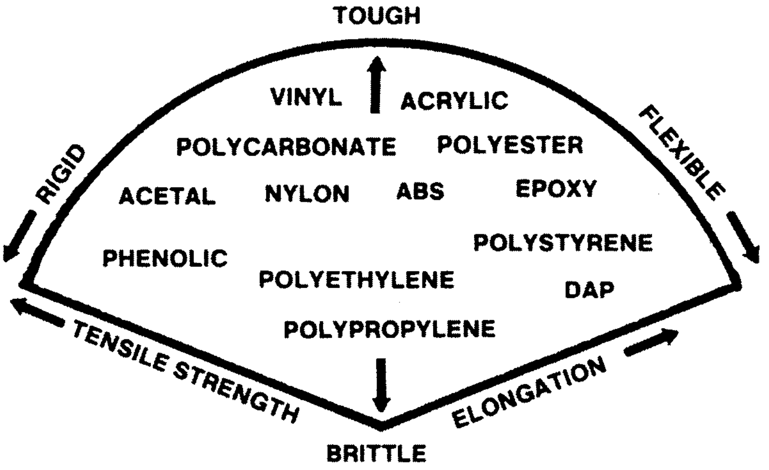


Figure 2.6 With modifications each of these plastics can be moved into literally any position in the pie section meeting different requirements

There are industry plastic classification systems such as ASTM D 4000. There is also ISO-1043 and others to meet different industry requirements. They provide a way to identify plastics for purchasing, fabricating, quality control, etc. Plastics are classified according to their origin and method of synthesis as well as fitting into systematic group categories such as plastic material type, modulus, nonrigid, semirigid, and rigid.

The first step in selecting a plastic for a product to be fabricated is to determine its complete requirements. Since there could be a tendency to overlook certain properties because they may appear to be insignificant or overlooked such as ensuring (obviously) that the product will perform during packaging, shipment, and/or in service. Selecting an optimal material for a given product must obviously be based on analysis of the requirements to be met. A simplified approach involves comparing the specific service requirements to the potential properties of a plastic (Table 2.9).

Table 2.9 Example for comparing cost and performance of nylon and die-cast alloys

Points for Comparison	Die-casting Alloys	Nylon
Cost of raw material/ton	Low	High
Cost of mold	High	Can be lower—no higher
Speed of component production	Slower than injection molding of nylon	Lower component production costs
Accuracy of component	Good	Good
Postmolding operations	Finishing—painting Paint chips off easily	Finishing—not required
Surface hardness	Low—scratches easily	Much higher. Scratch resistant.
Rigidity	Good to brittleness	Glass-reinforced grades as good or better
Elongation	Low	GR grades comparable; unfilled grades excellent
Toughness (flexibility)	Low	GR grades comparable; unfilled grades excellent
Impact	Low	All grades good
Notch sensitivity	Low	Low
Young's modulus (E)	Consistent	Varies with load
General mechanical properties	Similar to GR grades of 6/6 nylon	Higher compressive strength
Heat conductivity	High	Low
Electrical insulation	Low	High
Weight	High	Low
Component assembly	Snap fits difficult	Very good

The final selection of the product will often hinge on what is the best fabricating process for the product in question (Tables 2.10 and 2.11). Sometimes the necessity for certain elements in the product such as thin sections, long delicate inserts, requirements of exact concentricity, transparency, and/or extremely high accuracy of dimensions, make it desirable to use one technique of fabricating rather than another. Therefore, it is frequently necessary to reverse the usual selection procedure and determine the material to be used and the specific process and technique to be employed before the final design of the product.

Table 2.10 Examples of processes for plastic materials

Material Family	Injection	Compression	Transfer	Casting	Cold Molding	Coating	Structural Foam	Extrusion	Laminating	Sheet Forming	RP Molding FRP	Filament	Dip and Slush	Blow	Rotational
ABS	X						X	X		X				X	
Acetal	X						X	X		X				X	X
Acrylic	X			X		X		X	X	X				X	
Allyl		X	X	X	X	X			X			X			
ASA	X						X	X		X					
Cellulosic	X					X	X	X	X	X				X	X
Epoxy		X	X	X	X	X			X			X			
Fluoroplastic	X	X	X		X	X		X		X					X
Melamine-formaldehyde	X	X	X	X		X			X						
Nylon	X			X		X	X	X						X	X
Phenol-formaldehyde	X	X	X	X	X	X			X						
Poly (amide-imide)	X	X	X					X							
Polyarylether	X							X							
Polybutadiene	X		X					X						X	
Polycarbonate	X	X					X	X		X				X	X
Polyester (TP)	X					X		X						X	X
Polyester-fiberglass (TS)		X	X					X	X		X	X			X
Polyethylene	X	X				X	X	X	X	X				X	X
Polyimide	X	X				X		X							
Polyphenylene oxide	X						X	X							X
Polyphenylene sulfide	X	X				X									
Polypropylene	X						X	X		X				X	X
Polystyrene	X						X	X		X				X	X
Polysulfone	X	X						X		X					
Polyurethane (TS) (TP)	X	X	X	X		X	X	X	X	X				X	X
SAN	X						X	X	X	X					X
Silicone		X		X				X							
Styrene butadiene	X					X		X	X						
Urea formaldehyde		X							X						
Vinyl	X	X				X	X	X	X	X			X	X	X

Table 2.11 Examples of processes and plastic materials to properties

Plastic	Properties	Processes
Thermoplastics		
Polystyrene	Low cost, moderate heat distortion, good dimensional stability, good stiffness, impact strength	Injection molding Continuous laminating
Nylon	High heat distortion, low water absorption, low elongation, good impact strength, good tensile and flexural strength	Injection molding Blow molding, Rotational molding
Polycarbonate	Self-extinguishing, high dielectric strength, high mechanical properties	Injection molding
Styrene-acrylo-nitrile	Good solvent resistance, good long-term strength, good appearance	Injection molding
Acrylics	Good gloss, weather resistance, optical clarity, and color; excellent electrical properties	Injection molding Vacuum forming Compression molding Continuous laminating
Vinyls	Excellent weatherability, superior electrical properties, excellent moisture and chemical resistance, self-extinguishing	Injection molding Continuous laminating Rotational molding
Acetals	Very high tensile strength and stiffness, exceptional dimensional stability, high chemical and abrasion resistance, no known room temperature solvent	Injection molding
Polyethylene	Good toughness, light weight, low cost, good flexibility, good chemical resistance; can be "welded"	Injection molding Rotational molding Blow molding
Fluorocarbons	Very high heat and chemical resistance, nonburning, lowest coefficient of friction, high dimensional stability	Injection molding Encapsulation Continuous pultrusion
Polypropylene	Excellent resistance to stress or flex cracking, very light weight, hard, scratch-resistant surface, can be electroplated; good chemical and heat resistance; exceptional impact strength; good optical qualities	Injection molding Continuous laminating Rotational molding
Polysulfone	Good transparency, high mechanical properties, heat resistance, electrical properties at high temperatures; can be electroplated	Injection molding
Thermoset		
Polyesters Properties shown also apply to some polyesters formulated for thermoplastic processing by injection molding	Simplest, most versatile, economical and most widely used family of resins, having good electrical properties, good chemical resistance, especially to acids	Compression molding Filament winding Hand lay-up Mat molding Pressure bag molding Continuous pultrusion Injection molding Spray-up Centrifugal casting Cold molding Comoform[1] Encapsulation
Epoxies	Excellent mechanical properties, dimensional stability, chemical resistance (especially alkalis), low water absorption, self-extinguishing (when halogenated), low shrinkage, good abrasion resistance, very good adhesion properties	Compression molding Filament winding Hand lay-up Continuous pultrusion Encapsulation Centrifugal casting
Phenolics	Good acid resistance, good electrical properties (except arc resistance), high heat resistance	Compression molding Continuous laminating
Silicones	Highest heat resistance, low water absorption, excellent dielectric properties, high arc resistance	Compression molding Injection molding Encapsulation
Melamines	Good heat resistance, high impact strength	Compression molding
Diallyl phthalate	Good electrical insulation, low water absorption	Compression molding

Although there are literally thousands of plastics available, usually no single one will exhibit all desired properties in their proper relationships. Therefore a compromise among properties, cost, and fabricating process generally determines the material of construction.

There is a logical workable elimination approach to the selection of the correct plastic. Examples among the specific properties have been reviewed in this chapter that include chemical resistance (Table 2.12), color, crazing/cracking, electric/electronic, flame resistance, impact, odor/taste, radiation, temperature resistance (Figure 2.7), permeability (Table 2.13), transparency (Figure 2.8 and Table 2.14), weathering (Figure 2.9), moisture, etc.[1–3, 6, 133, 134, 367, 368, 426]

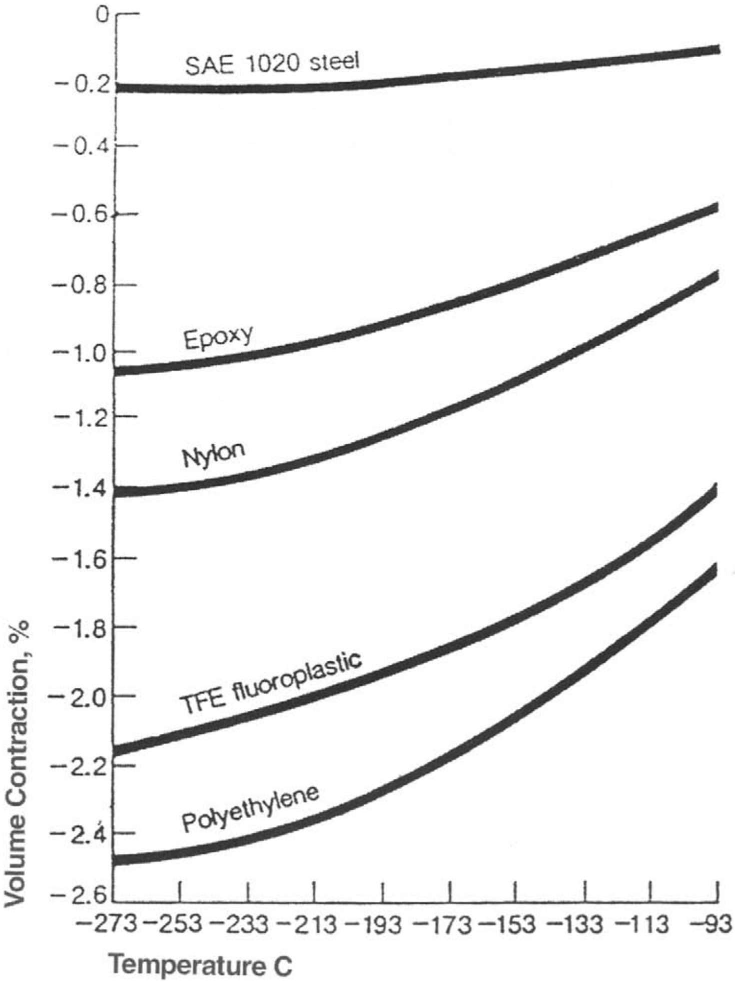


Figure 2.7 Examples of plastic contraction at low temperatures

Table 2.12 Chemical resistance of plastics (courtesy of Plastics FALLO)

	PLASTIC MATERIAL	Aromatic solvents		Aliphatic solvents		Chlorinated solvents		Weak bases and salts		Strong bases		Strong acids		Strong oxidants		Esters and ketones		24-hr. Water absorption
		temperature F																
		77	200	77	200	77	200	77	200	77	200	77	200	77	200	77	200	% change by weight
	Acetals	1-4	2-4	1	2	1-2	4	1-3	2-5	1-5	2-5	5	5	5	5	1	2-3	0.22 - 0.25
	Acrylics	5	5	2	3	5	5	1	3	2	5	4	4-5	5	5	5	5	0.2 - 0.4
	Acrylonitrile-Butadiene-Styrenes (ABS)	4	5	2	3-5	3-5	5	1	2-4	1	2-4	1-4	5	1-5	5	3-5	5	0.1 - 0.4
	Cellulose Acetates (CA)	2	3	2	3	3	4	2	3	3	5	3	5	3	5	5	5	2 - 7
	Cellulose Acetate Propionates (CAP)	4	5	1	3	3	4	1	2	3	5	3	5	3	5	5	5	1.3 - 2.8
	Diallyl Phthalates (DAP, filled)	1-2	2-4	2	3	2	4	2	3	2	4	1-2	2-3	2	4	3-4	4-5	0.2 - 0.7
	Epoxies	1	2	1	2	1-2	3-4	1	1-2	1	2	2-3	3-4	4	4-5	2	3-4	0.01 - 0.10
	Ethylene Copolymers (EVA) (Ethylene-Vinyl Acetates)	5	5	5	5	5	5	1	2	1	5	1	5	1	5	2	5	0.05 - 0.13
Fluorocarbons	Ethylene/Tetrafluoroethylene Copolymers (ETFE)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	<0.03
	Fluorinated Ethylene Propylenes (FEP)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	<0.01
	Perfluoroalkoxies (PFA)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	<0.03
	Polychlorotrifluoroethylenes (CTFE)	1	1	1	1	3	4	1	1	1	1	1	1	1	1	1	1	0.01 - 0.10
	Polytetrafluoroethylenes (TFE)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
	Ionomers	2	4	1	4	4	4	1	4	1	4	2	4	1	5	1	4	0.1 - 1.4
	Melamines (filled)	1	1	1	1	1	1	2	3	2	3	2	3	2	3	1	2	0.01 - 1.30
	Nitriles (high barrier alloys of ABS or SAN)	1	4	1	2-4	1-4	2-5	1	2-4	1	2-4	2-5	5	3-5	5	1-5	5	0.2 - 0.5
	Nylons	1	1	1	1	1	2	1	2	2	3	5	5	5	5	1	1	0.2 - 1.9
	Phenolics (filled)	1	1	1	1	1	1	2	3	3	5	1	1	4	5	2	2	0.1 - 2.0
	Polyallomers	2	4	2	4	4	5	1	1	1	1	1	3	1	4	1	3	<0.01

continued

Table 2.12 continued

PLASTIC MATERIAL	Aromatic solvents		Aliphatic solvents		Chlorinated solvents		Weak bases and salts		Strong bases		Strong acids		Strong oxidants		Esters and ketones		24-hr. Water absorption
	temperature F																
	77	200	77	200	77	200	77	200	77	200	77	200	77	200	77	200	% change by weight
Polyamide-imides	1	1	1	1	2	3	1	1	3	4	2	3	2	3	1	1	0.22 - 0.28
Polybutylenes (PB)	3	5	1	5	4	5	1	2	1	3	1	3	1	4	1	3	<0.01 - 0.3
Polycarbonates (PC)	5	5	1	1	5	5	1	5	5	5	1	1	1	1	5	5	0.15 - 0.35
Polyesters (thermoplastic)	2	5	1	3-5	3	5	1	3-4	2	5	3	4-5	2	3-5	2	3-4	0.06 - 0.09
Polyesters (thermoset-glass fiber filled)	1-3	3-5	2	3	2	4	2	3	3	5	2	3	2	4	3-4	4-5	0.01 - 2.50
Polyethylenes (LDPE-HDPE — low-density to high-density)	4	5	4	5	4	5	1	1	1	1	1-2	1-2	1-3	3-5	2	3	0.00 - 0.01
Polyethylenes (UHMWPE — ultra high molecular weight)	3	4	3	4	3	4	1	1	1	1	1	1	1	1	3	4	<0.01
Polyimides	1	1	1	1	1	1	2	3	4	5	3	4	2	5	1	1	0.3 - 0.4
Polyphenylene Oxides (PPO) (modified)	4	5	2	3	4	5	1	1	1	1	1	2	1	2	2	3	0.06 - 0.07
Polyphenylene Sulfides (PPS)	1	2	1	1	1	2	1	1	1	1	1	1	1	2	1	1	<0.05
Polyphenylsulfones	4	4	1	1	5	5	1	1	1	1	1	1	1	1	3	4	0.5
Polypropylenes (PP)	2	4	2	4	2-3	4-5	1	1	1	1	1	2-3	2-3	4-5	2	4	0.01 - 0.03
Polystyrenes (PS)	4	5	4	5	5	5	1	5	1	5	4	5	4	5	4	5	0.03 - 0.60
Polysulfones	4	4	1	1	5	5	1	1	1	1	1	1	1	1	3	4	0.2 - 0.3
Polyurethanes (PUR)	3	4	2	3	4	5	2-3	3-4	2-3	3-4	2-3	3-4	4	4	4	5	0.02 - 1.50
Polyvinyl Chlorides (PVC)	4	5	1	5	5	5	1	5	1	5	1	5	2	5	4	5	0.04 - 1.00
Polyvinyl Chlorides-Chlorinated (CPVC)	4	4	1	2	5	5	1	2	1	2	1	2	2	3	4	5	0.04 - 0.45
Polyvinylidene Fluorides (PVDF)	1	1	1	1	1	1	1	1	1	2	1	2	1	2	3	5	0.04
Silicones	4	4	2	3	4	5	1	2	4	5	3	4	4	5	2	4	0.1 - 0.2
Styrene Acrylonitriles (SAN)	4	5	3	4	3	5	1	3	1	3	1	3	3	4	4	5	0.20 - 0.35
Ureas (filled)	1	3	1	3	1	3	2	3	2	3	4	5	2	3	1	2	0.4 - 0.8

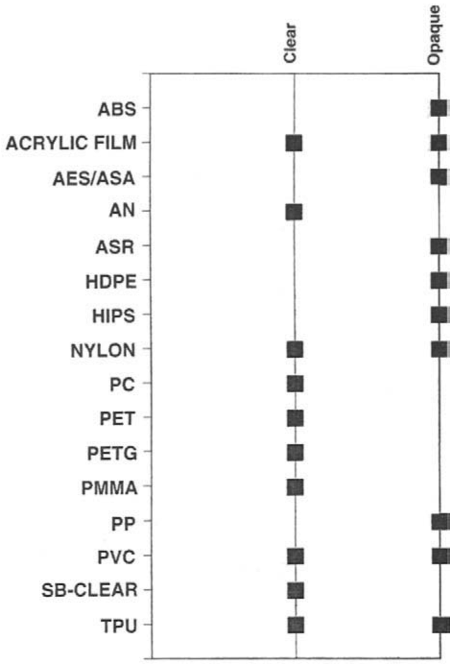


Figure 2.8 Guide to clear and opaque plastics

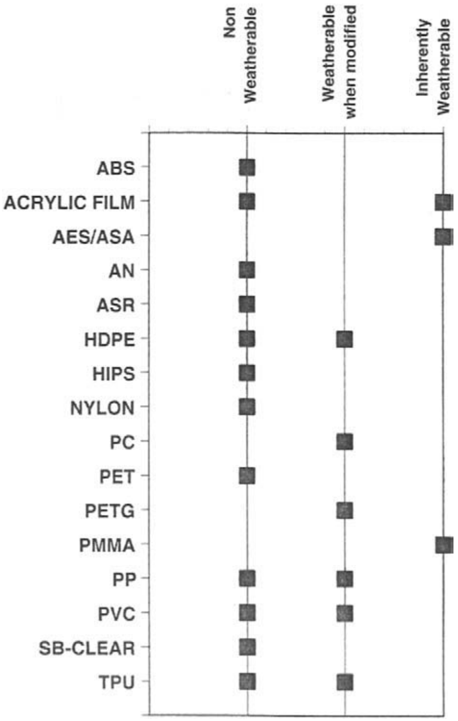


Figure 2.9 Examples of the weatherability of plastics

Table 2.13 Examples of permeability for plastics

Type of Polymer	Specific Gravity (ASTM D 792)	Water Vapor Barrier	Gas Barrier	Resistance to Grease and Oils
ABS (acrylonitrile butadiene styrene)	101–1.10	Fair	Good	Fair to good
Acetal—homopolymer and copolymer	1.41	Fair	Good	Good
Acrylic and modified acrylic	1.1–1.2	Fair	——	Good
Cellulosics acetate	1.26–1.31	Fair	Fair	Good
Butyrate	1.15–1.22	Fair	Fair	Good
Propionate	1.16–1.23	Fair	Fair	Good
Ethylene vinyl alcohol copolymer	1.14–1.21	Fair	Very good	Very good
Ionomers	0.93–0.96	Good	Fair	Good
Nitrile polymers	1.12–1.17	Good	Very good	Good
Nylon	1.13–1.16	Varies	Varies	Good
Polybutylene	0.91–0.93	Good	Fair	Good
Polycarbonate	1.2	Fair	Fair	Good
Polyester (PET)	1.38–1.41	Good	Good	Good
Polyethylene				
Low density	0.910–0.925	Good	Fair	Good
Linear low density	0.900–0.940	Good	Fair	Good
Medium density	0.926–0.940	Good	Fair	Good
High density	0.941–0.965	Good	Fair	Good
Polypropylene	0.900–0.915	Very good	Fair	Good
Polystyrene				
General purpose	1.04–1.08	Fair	Fair	Fair to good
Impact	1.03–1.10	Fair	Fair	Fair to good
SAN (styrene acrylonitrile)	1.07–1.08	Fair	Good	Fair to good
Polyvinyl chloride				
Plasticized	1.16–1.35	Varies	Good	Good
Unplasticized	1.35–1.45	Varies	Good	Good
Polyvinylidene chloride	1.60–1.70	Very good	Very good	Good

Table 2.14 Examples of transparent plastics

Generic family	**Notable characteristics**
Transparent ABS	Good impact properties, good processibility
Acrylic (PMMA)	Excellent resistance to outdoor exposure, crystal clarity
Allyl diglycol carbonate	Good abrasion/chemical resistance, thermoset
Cellulosics	Heat sensitive, limited chemical resistance, good toughness
Nylon, amorphous	Excellent abrasion resistance, moisture sensitive
PET, PETG	Good barrier properties, not weatherable, clarity dependent on processing, orientation greatly increases physical properties
Polyarylate	Excellent UV resistance, high heat distortion
Polycarbonate	Excellent toughness, good thermal/flammability characteristics
Polyetherimide	Good chemical/solvent resistance, good thermal/flammability properties, inherent high color
Polyphthalate carbonate	Good thermal properties, autoclavable
Polyethersulfone	Excellent thermal stability, resists creep
Poly-4-methylpentene-1	UV/moisture sensitive, high crystalline melting point, lowest density o all thermoplastics
Polyphenylsulfone	Excellent thermal stability, resists creep, inherent high color
Polystyrene	Excellent processibility, poor UV resistance, brittle
Polysulfone	Excellent thermal/hydrolytic stability, poor weatherability/impact strength
PVC, rigid	Excellent chemical resistance/electrical properties, weatherable, decomposition evolves HCl gas
Styrene acrylonitrile	Good stress-crack and craze resistance, brittle
Styrene butadiene	Good processibility, no stress whitening
Styrene maleic anhydride	Higher-heat styrenic, brittle
Styrene methyl methacrylate	Good processibility, slightly improved weatherability
Thermoplastic urethane, rigid	Excellent chemical/solvent resistance, good toughness

3 FABRICATING PRODUCT

Overview

The profound impact of plastic products to people worldwide and in all industries worldwide includes the intelligent application of processing these plastics. These plastics utilize the versatility and vast array of inherent plastic properties as well as the usual high-speed/relative low-energy processing techniques. The result has been the development of millions of cost-effective products used worldwide that in turn continue to have exceptional benefits for people and industries worldwide.

In a market economy, which is to say the real world that is ruled by competition, processed plastics will be employed only in applications where they can be expected to bring an overall economic advantage compared with other competing products. In this connection it is well to note that the biggest competitor to a given plastic may be another plastic with their respective processing techniques. On the basis of an overall benefit assessment taking in the full service of a processed plastic product, it has been shown in millions of cases worldwide that the use of processed plastics not only makes economic sense but also makes a contribution toward conserving resources.

There are many factors that are important in making plastic products the success it has worldwide. One of these factors involves the use of the availability of different fabricating processes. All processes fit into an overall scheme that requires interaction and proper control of operations based on material requirements. Thus fabricating is an important part of the overall project to produce acceptable plastic products. It highlights the flow pattern for the fabricator (manufacturer) to be successful and profitable. Recognize that first to market with a new product captures 80% of market share. Factors such as good engineering, process control, etc. are very important but only represent pieces of the "pie." Philosophical many different ingredients blend together to produce profitable products. Fabricating is one of the important main ingredients.

With continuing new developments in equipment (and plastics) their quality performance and output rate improves and overhead costs are reduced. Result has been the industry worldwide continues to be more productive even though the economy has its ups and downs.[135, 136, 248]

In order to understand potential problems and solutions of fabrication, it is helpful to consider the relationships of machine capabilities, plastics processing variables, and product performance.[1] In turn, as an example, a distinction has to be made here between machine conditions and processing variables. For example, machine conditions include the operating temperature and pressure, mold and die temperature, machine output rate, and so on. Processing variables are more specific, such as the melt condition in the mold or die, flow rate vs. temperature and so on (Chapter 1).

Fabricating products involves conversion processes that may be described as an art. Like all arts they have a basis in science and one of the short routes to processing improvement is a study of the relevant sciences (as reviewed throughout this book that range from the different plastic melt behaviors to fabricating all size and shape products to meet different performance requirements). The plastic-processing target is to take the plastic in the form of pellets, powders, granules, liquids, etc. and converting them into useful products usually through a screw plasticator.

Processing of plastic is an art of detail. The more you pay attention to details, the fewer problems develop in the process. If it has been running, it will continue running well unless a change occurs. Correct the problem and do not compensate. It may not be an easy task, but understanding what you have equipment-wise can help. Common features of these different processes is as follows:

(a) **Mixing and melting**: This stage takes the plastic and in turn produces a homogeneous melt (Chapter 1). This is often carried out in a screw plasticator or compounder, where melting takes place as a result of heat conducted through the barrel wall and heat generated in the plastic by the action of shear via the screw. Homogeneity is called for at the end of this stage, not only in terms of material but also in respect to temperature.

(b) **Tooling**: When processing plastics some type of tooling is required. These tools include molds and dies for shaping and fabricating products. They have some type of female and/or male cavity into or through which a molten or rigid plastic moves usually under heat and pressure. They are used in processing many different materials to form desired shapes and sizes. They can comprise of many moving parts requiring high quality metals and precision machining. Some molds and dies cost more than the primary processing machinery with the usual approaching half the cost of the primary machine (Chapter 17).

(c) **Melt transport & shaping**: In a screw plasticator the next step would be to build up an adequate pressure in the plasticator so that it will produce the desired shape to be fabricated. In an injection molding process pressure is applied to force the melt into a mold that defines the product shape in three dimensions (Chapter 4). In an extruder the die (that initiates the shape) can vary from a simple cylindrical shape to a complex crosshead profile shape (Chapters 5).

(d) **Drawing, blowing, and forming**: There are processes that use a screw plasticator melt to stretch the melt to produce orientation and desired shape, as in blow molding, thermoforming, rotational molding, and foaming (Chapters 6, 7, 8, 13).

(e) **Coating and Casting**: With screw plasticator or other systems the melt provides coatings and castings as reviewed in Chapters 10, 11, 16.

(f) **Non-screw plasticating**: Reactive mixing provides the melt in reaction injection molding (Chapter 12). In compression molding the usual material is precompounded or preimpregnated prior to being placed in or around a mold (Chapters 14 and 15).

(g) **Finishing**: The final stage after a process fabricates a product usually does not require secondary operations. However, there are materials or products that may require annealing, sintering, coating, assembly, decoration, etc. (Chapter 18).

Processing techniques range from the unsophisticated (high labor costs with low capital costs) to sophisticated (zero or almost zero labor costs with very high capital costs). Production quantity, the material being processed, the available equipment, and the total cost govern decisions on the appropriate technique. Small quantities are usually produced with an unsophisticated approach.

Many fabricating processes are employed. Which process to use depends upon the nature and requirements of the plastic to be processed, properties required in the finished product, cost of the process, speed, and volume to be produced. Some processes can be used with many kinds of plastics; others require specialized processes. Recognize that the final actual properties of a processed plastic for an application are directly related to how the plastics are processed. If process controls are not properly set up, followed, and continually rechecked to insure meeting part performance requirements, products could be improperly processed. This quality control requirement^3 on processing plastics applies to all products.

With the beginning of a deeper understanding of process mechanisms and their underlying physical laws and close cooperation between theorists and practical people, has processing technology and machinery design made any real progress. This progress will always continue since new plastics and new processing techniques develop. There are the basic fabricating processes (Chapter 4–16) however many different modifications continue to be developed (Table 3.1).

Table 3.1 Examples of names of plastic fabricating processes

adiabatic extrusion
adiabatic injection molding
adiabatic processing
advanced composite molding
air floatation
airmold gas-assist injection molding
autoclave adhesive bonding
autoclave molding
autogeneous extrusion
automatic extrusion
automatic molding
automatic processing
auxiliary equipment
backmolding (Hinterspritzen)
bag molding
biaxially-oriented extrusion
biaxially-oriented molding
bladder molding
blister process
blow molding (different types)
blown film
BMC injection molding
bridge reinforced plastic
bulk molding compound
cable extrusion
calendering (different types)
carded package
carousel molding
casting (different types)
C-clamp injection molding
cellular plastic molding
cellular chemical blow molding
centrifugal casting
centrifugal molding
ceramic-plastic molding
chemical vapor deposition
cladding
closed molding
coating (different types)
coextruded foamed blow molding
coextrusion
coextrusion capping
coining
coinjection foam molding
coinjection molding
cold flow molding
cold forming
cold heading
cold molding
cold press molding
cold stamping
cold working,
combiform
comoforming cold molding
compounding
compound molding
composite molding
Compreg molding
compression-injection molding
compression molding (different types)
computer-aided extrusion
computer-aided molding
computer aided processing
contact molding
contact pressure molding
continuous coating
continuous fiber spinning
continuous injection molding
continuous laminating
continuous molding
continuous strip molding
controlled density molding
copolymer molding
corrugated pipe extrusion
corrugated multilayer pipe extrusion
counter pressure intrusion
counter pressure molding
crossflow molding
cross laminating
decompression molding
devolatilizing extrusion
devolatilizing molding
die casting
die-slide molding
dip casting
dip forming
dip blow molding
dip molding
dip coating
doctor blade coating
dose molding
dosing extrusion
dosing molding
double-daylight molding
double shot molding
draw working
dry blend molding
elastomer molding

continued

Table 3.1 continued

electric operating injection molding
electroforming
electron beam polymerization,
electroplating
electrostatic spray
embedding
embossing
encapsulation
expandable polystyrene (and other plastics)
extruder (different types)
extrusion blow molding
extrusion compounding
extrusion molding
female forming
fiber forming
fiber placement molding
fiber reinforced molding
fiber spinning (wet, dry, jet, etc.)
fibrillation
FIFO injection molding
filament placement
filament winding (different types)
film casting
film extrusion
flame spraying
flat film
flexible plunger molding
flocculation
flocking or floc spraying
flow molding
fluidized bed
foamed casting (different types)
foamed extrusion
foamed-in-place
foamed-in-place gasketing
foamed molding (many different types such as injection, extrusion, calendering, casting, blow molding, etc.)
foamed reservoir molding
forging
forming (different types)
forming plastic-metal
forming scrapless
forming solid phase pressure
foundry molding
Fourdrinier
four-station molding
free extrusion
free molding
fusible core molding
gas assist molding
gas assist molding without gas channels
gas blow molding
gas counter-pressure injection molding
gas counter pressure molding
gas injection foam molding
gas injection molding
gear pump extrusion
gear pump injection molding
geometric forming
geometric molding
glass fiber spinning
glass mat reinforced molding
granular paint injection
graphitized fiber spinning
grease-free injection molding
group transfer polymerization
grow molding
hand layup molding
heat-cured rubber molding
heat sealing
high density molding
high frequency molding
high pressure foam molding
high pressure injection molding
high pressure molding
horizontal extrusion
horizontal injection molding
horizontal wheel blow molding
horizontal wheel extrusion
horizontal wheel forming
horizontal wheel molding
hot melt molding
hot stamping
hot working
hybrid-electric operating injection molding
hydroclave molding
hydromechanical clamp injection molding
impregnation molding
impulse sealing
infusion molding
injection blow molding
injection compounding
injection-compression molding
injection-die pultrusion
injection molding (different types)
injection molding-prepressurized cavity
injection molding stamping
injection transfer molding
in-line slot extrusion/ thermoforming
in-mold coat molding
in-mold decorating
intermediate pressure molding
interpenetrating blend molding
intrinsic molding
inplace molding
insert injection molding
insert molding
intrusion-flow molding
inverse lamination
investment casting
isotactic molding/pressure
jet molding
jet spinning
lagging molding
laminated molding
layup molding
leatherlike molding
Lego molding
LIFO injection molding
liquid crystal extrusion
liquid crystal molding
liquid curing extrusion
liquid injection molding
liquid silicone rubber injection molding
liquid transfer molding
lost wax molding
low pressure foam molding
low-pressure injection molding
low-pressure inverted-force injection molding
low pressure molding
low-profile resin molding
machining
male forming
manifold molding
manual extrusion
manual molding
manual processing
marbleize molding
Marco pressure molding
Marco vacuum molding
Marco vacuum-pressure molding
matched die molding
mechanical clamping injection molding
melt lamination
melt roll
metal injection molding
metallizing
metal powder injection molding

Table 3.1 continued

metal powder molding
metal spraying
microencapsulation
molding with rotation
melt processable rubber process
melt processable wood process
metal-plastic molding
molding (compression, injection, bag, etc.)
molecular density molding
multi-color injection molding
multi-component injection molding
multi-compound molding
multi-injection molding
multilayer blow molding
multilayer foam extrusion
multilayer foam injection molding
multilayer solid-foam extrusion
multilayer solid-foam molding
multilayer solid extrusion
multilayer solid molding
multilive feed molding
multi-material molding
multi-station forming
multi-station molding
multiwall molding
netting
netting extrusion
non-porous metal-plastic molding
notched die molding
off-center injection molding
offset extrusion
offset molding
one-shot molding
open molding
orientaton process (different types)
oriented extrusion
open frame forming
oriented molding
oscillating die extrusion
overcoat extrusion
overcoat lamination
overcoat molding
packaging (different types)
parallel laminating
pelletizing extrusion
perforating
photopolymerization
physical blow molding
pinhold-free coating
pipe blow molding
pipe extrusion
plastic-concrete process
plastic-metal molding
plunger molding
polyurethane foam molding
poromeric molding
post-consumer extrusion
post-consumer molding
post forming
powder molding
potting
powder injection molding
preform molding
premolding
prepolymer molding
prepreg molding (different types)
press lamination
pressure bag molding
pressure fabrication
pressure forming
pressure lamination
processing-artistic
processing-basics
profile extrusion
pullforming
pulp molding
pulse molding
pultrusion molding
pyrolysis carbon fiber spinning
ram extrusion
ram injection molding
ram molding
rapid prototype molding
radio frequency molding
reaction injection molding
reactive polymer processing
recycled compound molding
reinforced foam molding
reinforced plastics (different types)
reinforced reaction injection molding
reinforced reaction molding
reinforced rotational molding
resin transfer molding
rock-and-roll molding
roll covering
rolling
roll milling
room temperature molding
rotary core molding
rotary molding
rotary table molding
rotating die extrusion
rotating mold turret injection molding
rotational casting
rotational molding
rotomold
rotomold ovenless
rotovinyl sheet
rubber insert molding
salt bath process (different types)
sandwich molding
scrapless forming,
scrapeless molding
screw molding
screw plunger transfer molding
Scorim molding
scrimp
semiautomatic extrusion
semiautomatic molding
semiautomatic processing
sheet extrusion
sheet molding compound
shell molding
shrink wrap
shrink wrap bag processing
shuttle forming
shuttle molding
sintering
skin molding
skiving
sliding insert molding
slip forming
slot extrusion
slush molding
smart-card/closed-loop controlled injection molding
SMC continuous fiber molding
SMC directionally oriented molding
SMC randomly oriented molding
soluble core injection molding
soluble core molding
solution casting
solvent bonding
solvent casting
solvent molding
spin casting
spinneret fiber forming
spinning
spline process
spraying (different types)
spray-up molding
spread coating
spreader molding
squeeze molding
stack blow molding
stack injection molding
stamping

continued

Table 3.1 continued

staple fiber spinning
steam chamber-filament spinning
stretch blow molding
strip molding
structural casting
structural foam molding
structural reaction injection molding
stuffer injection molding
supperplastic forming
syntactic foaming
tape placement wrapped molding
tenter frame forming
thermal expansion molding
thermoforming (different types)
thermoplastic extrusion
thermoplastic injection molding
thermoplastic molding
thermoplastic structural foam molding
thermoset extrusion
thermoset injection molding
thermoset molding
thermoset structural foam molding
thick compound molding
thin-wall injection molding
thixomolding
three-platen injection molding
three-station molding
toggle clamp injection molding
tooling
torpedo molding
transfer molding
trickle impregnation
tube extrusion
tubing-heat shrinkable
turnkey injection molding
twin-sheet forming
twin-sheet thermoforming (different types)
two-color injection molding
two-color molding
two-platen clamp injection molding
two-stage injection molding
two-station molding
ultrasonic fabrication
ultrasonic vacuum bag molding
ultraviolet molding
vacuum bag molding
vacuum casting
vacuum coating
vacuum forming
vacuum hot forming
vacuum press molding
vacuum pressure bag molding
variable pressure foaming
vented extrusion
vented injection molding
vertical extrusion
vertical injection molding
vertical wheel extrusion
vertical wheel forming
vertical wheel injection molding
vibration gas injection molding
vibration molding
vinyl dispersion
vinyl plastisol forming
viscous molding
void-plastic impregnation
vulcanization
waste molding
welding
wet layup molding
wire coating
wire coating extrusion
wheel blow molding
wood-plastic impregnation molding
wood pulp-plastic extrusion

The long list of methods used to process plastics in Table 3.1 includes all types of basic and specialty processes that have been developed over the past century. Included are also those that have different names for the same process. The different names are used for diversified reasons that include:

1 used in different industries that have their method of identifying a process based on their market requirements,
2 an old process that may be basically the same or slightly modified requiring a more modern name,
3 promoting new ideas requiring a name to symbolize a new generation, and others.

There are overlapping of terms such as molds, dies, and tools and also terms such as molding, embedding, casting, potting, etc. There are continuous and noncontinuous extrusion processing methods. Injection molding includes gas and water injection, insert molding, micro-molding, etc. This situation does not cause a problem or should not affect anyone's thinking when examining processes. As one may recognize throughout the world and particularly in the industrialized nations, one might say that there are words or situations that could have more than one meaning. The important message here is that it may be important for you to be very specific when describing a process (also materials, designs, and so on).

There are the major families of processing, based on the amount of plastic processed in USA and worldwide. They are extrusion (EX) consumes approximately 36wt% of all plastics, injection molding (IM) follows by consuming 32%, blow molding at 10%, calendering at 8%, coating at 5%, compression molding at 3%, and others at 3%. Thermoforming, can be considered the fourth major process used; consumes about 30% of the extruded sheet and film that principally goes into packaging.

When analyzing processes to produce all types of products, at least 65wt% of all plastics require some type of specialized compounding. They principally go through compounding extruders, usually twin-screw extruders (Chapter 5), before going through equipment such as injection molding machines, extruders, and blow molding machines to produce products.

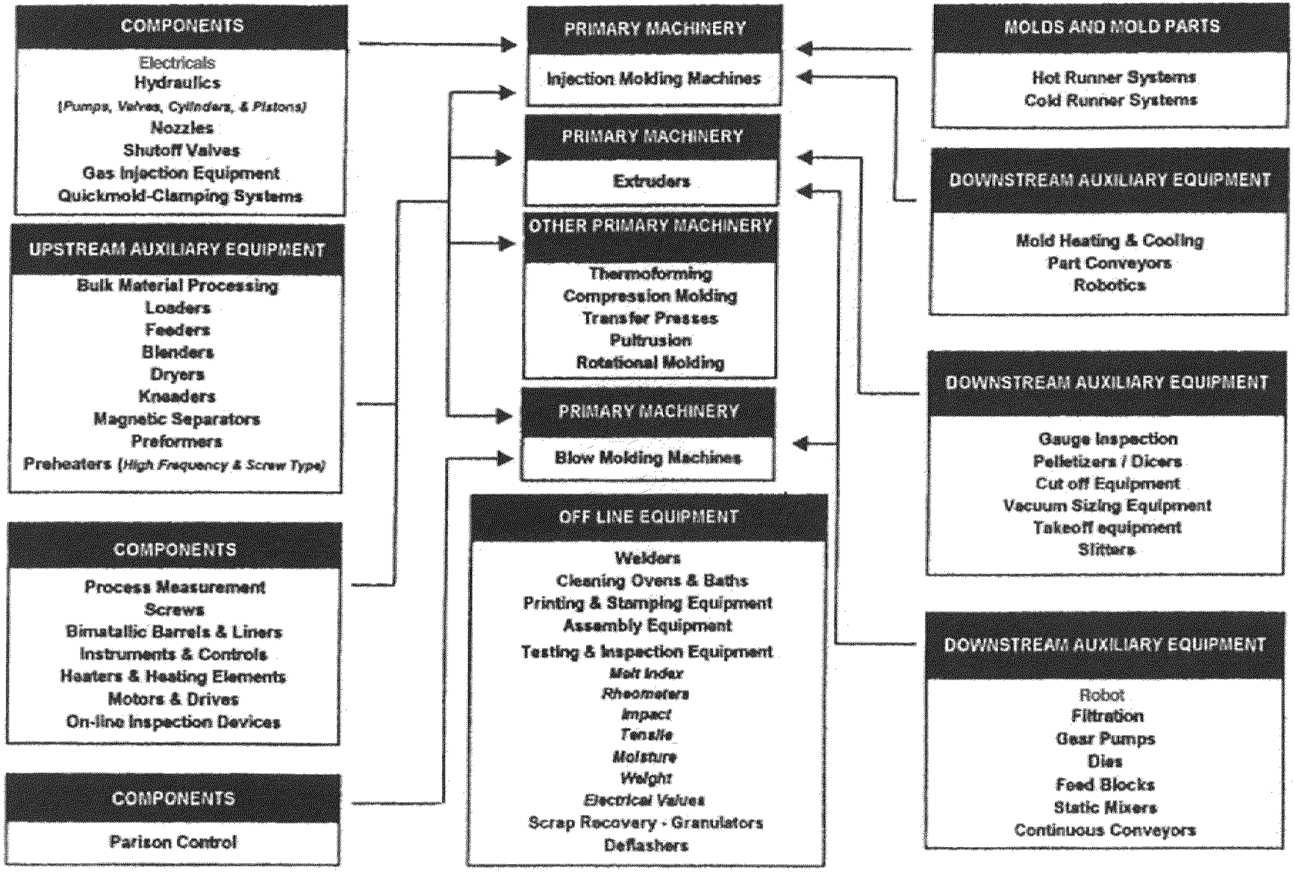
It is estimated that in USA there are about 17,000 extruders, 70,000 injection molding machines, and 6,000 blow molding machines producing about one-third of the world's plastic products. For the 80,000 IMMs in USA the usual report shows that 30% are under five years old, at least 35% are five to ten years old, and the rest are more than ten years old.

In USA machinery sales yearly demand normally is about $1.5 billion (not taking into account the depressed years that occur at least every 10 to 20 years. IMM is the largest category that accounts for at least 50% of all the machinery sales. Blow molding (extrusion and injection types) machines are now at about $505 million, extrusion reaches $440 million, and thermoforming reaches $455 million. There are now over 350 USA machinery builders with about five having over 50% of sales.[136–139]

The plastics industry is comprised of mature practical and theoretical technology. Improved understanding and control of materials and fabricating processes (Table 3.2) have significantly increased product performances and reduced their variability resulting in good to excellent return on investments (ROIs).[140]

Plastic processes permit the fabrication of products whose manufacturing would be very costly or difficult if not impossible in other materials. Processors must routinely keep up to date on developments with the more useful plastics and acquire additional information on how to process them. The emphasis throughout this book has been that it is not difficult to design and fabricate with plastics

Table 3.2 Flow chart in fabricating plastic products (courtesy of Adaptive Instruments Corp.)


COMPONENTS
Electricals
Hydraulics
(Pumps, Valves, Cylinders, & Pistons)
Nozzles
Shutoff Valves
Gas Injection Equipment
Quickmold-Clamping Systems
UPSTREAM AUXILIARY EQUIPMENT
Bulk Material Processing
Loaders
Feeders
Blenders
Dryers
Kneaders
Magnetic Separators
Preformers
Preheaters (High Frequency & Screw Type)
COMPONENTS
Process Measurement
Screws
Bimetallic Barrels & Liners
Instruments & Controls
Heaters & Heating Elements
Motors & Drives
On-line Inspection Devices
COMPONENTS
Parison Control
PRIMARY MACHINERY
Injection Molding Machines
PRIMARY MACHINERY
Extruders
OTHER PRIMARY MACHINERY
Thermoforming
Compression Molding
Transfer Presses
Pultrusion
Rotational Molding
PRIMARY MACHINERY
Blow Molding Machines
OFF LINE EQUIPMENT
Welders
Cleaning Ovens & Baths
Printing & Stamping Equipment
Assembly Equipment
Testing & Inspection Equipment
Melt Index
Rheometers
Impact
Tensile
Moisture
Weight
Electrical Values
Scrap Recovery - Granulators
Deflashers
MOLDS AND MOLD PARTS
Hot Runner Systems
Cold Runner Systems
DOWNSTREAM AUXILIARY EQUIPMENT
Mold Heating & Cooling
Part Conveyors
Robotics
DOWNSTREAM AUXILIARY EQUIPMENT
Gauge Inspection
Pelletizers / Dicers
Cut off Equipment
Vacuum Sizing Equipment
Takeoff equipment
Slitters
DOWNSTREAM AUXILIARY EQUIPMENT
Robot
Filtration
Gear Pumps
Dies
Feed Blocks
Static Mixers
Continuous Conveyors

and to produce many different sizes and shapes of thermoplastic (TP) and thermoset (TS) commodities and engineering plastics, whether unreinforced or reinforced. The bases of material and process selection should be product performance requirements, shape, dimensional tolerances, processing characteristics, production volume, and cost.[482]

Extruders can be classified as:

1 continuous with single-screws (single and multistage) or multi-screws (twin-screw, etc.),
2 continuous disk or drum that uses viscous drag melt actions (disk pack, drum, etc.) or elastic melt actions (screwless, etc.), and
3 discontinuous that use ram actions [thermoset (TS) plastics, rubbers/elastomers, and very low viscosity thermoplastics (TPs)] and reciprocating actions (injection molding, etc.).

Injection molding (IM) is basically a discontinuous extruder. It identifies a process where a liquid or solid form of plastic is transferred into a mold or other tool in order to fabricate products. This IM process has subdivisions that include conventional IM, foam IM, gas-assist IM, water-assist IM, coinjection molding, and continuous IM. There are other molding processes that have their specific names and very diversified methods of operation. They include reaction injection molding (RIM), liquid injection molding (LIM), resin transfer molding (RTM), structural foam molding, expandable polystyrene molding, and liquid casting.

There are differences in casting, encapsulation, and potting terms however they are often interchangeable; they interrelate very closely to describe processes and performances. Both TPs and TSs are used. As an example there are reactive TS liquids that are often used to form solid shapes. Such plastic systems harden or cure at room temperature or at elevated temperatures because of the irreversible crosslinking of rather complex molecular structures. This is different from the hardening of plastics in solution, which harden when the solvent is evaporated. The hardening of the reactive plastics produces no by-products, such as gases, water, and/or solvents. When reactive plastics are used as impregnates, they are sometimes called solventless systems. However, there are plastics and certain additives that release gases and may require degassing during processing.

To help in quickly evaluating what machinery is available worldwide that will meet your requirements Plastics Technology publications has set up an online website (www.plasticstechnology.com). This action follows their annual *Processing Handbook and Buyers' Guide* that has been published for many decades.

Even though modern fabricating machines with all its ingenious microprocessor control technology is in principle suited to perform flexible tasks, it nevertheless takes a whole series of peripheral auxiliary equipment to guarantee the necessary degree of flexibility (Chapter 18). Examples of this action includes:

1 raw material supply systems;
2 mold/die transport facilities;
3 mold/die preheating banks;
4 mold/die changing devices that includes rapid clamping and coupling equipment;
5 plasticizer cylinder changing devices;
6 fabricated product handling equipment, particularly robots with interchangeable arms allowing adaptation to various types of production; and
7 transport systems for finished products and handling equipment to pass products on to subsequent production stages.

Processing and patience

The startup of fabricating lines usually requires changing equipment settings. When making processing changes, allow enough time to achieve a steady state in the complete line before collecting data. It may be important to change one processing parameter at a time. As an example with one change such as screw speed, temperature zone setting, or another parameter, allow time to achieve a steady state prior to collecting data.

A major cost advantage for fabricating plastic products in production has been and will continue to be their usual relatively low processing cost. The most expensive part of practically all products is the cost of plastics. Since the material value in a plastic product is roughly up to one-half (possibly up to 90%) of its overall cost, it becomes important to select a candidate material with extraordinary care particularly on long production runs. Cost to fabricate usually represents about 5% (usual maximum 10%) of total cost.

For those believing plastics are low cost, it is a misconception; they are not. There are so-called low cost types (commodity types) when compared to the more expensive engineering types (Chapter 1). Important that one recognizes that it is economically possible to process a more expensive plastic because it provides for a lower processing cost. By far the real advantage to using plastics to produce many low-cost products is their low weight with their low processing costs.

When a plastic fabricator considers updating a fabricating facility with a state-of-the-art operation the usual operating factors already in use require reviews and up dates such as material handling and services (electric power, water cooling, etc.) to machine safety operations. Estimating cost and site location are two initial pitfalls that must be avoided. One can overestimate difficulties or underestimate challenges with results ranging from expensive to disastrous financial situations. However these problems can be avoided by assembling a qualified high-quality team that includes an architect, facility contractor, and if needed a consulting engineer that has experience with plastics manufacturing plants.

Regarding choosing the correct site is often the most critical decision in the process. This action contains various variables such as make sure there is adequate access to power and water. Consider what combination of highway and rail access will work best for receiving raw materials and shipping products. Check local zoning laws such as permitting silos or cooling towers. Determine if the local labor supply is adequate for the type of people required. Select a site that permits future expansion. Design the building so that expansion can be accomplished without interrupting production. Wiring and piping systems should be designed with expansion possibilities. More loading dock space should be planned. Parking area must be easy to enlarge. New venting and air conditioning technology can help reduce operating costs significantly (Chapter 18).

Processor certification

Available are national skills certification programs by different organizations worldwide to certify the skills and knowledge of the plastic industry processor machine operators. An example is SPI's Industries National Certification in Plastics (NCP) program. It includes:

1 to identify job-related knowledge, skills, and abilities,
2 to establish a productive performance standard,
3 to assess and recognize employees who meet the standard; and
4 to promote careers in the plastics industries.

The examination includes: basic equipment process and program control; prevention and corrective action on primary and secondary equipment, delivery of plastic materials, material handling, storage, quality assurance; machinery and plant safety; handling tools and equipment, packaging fabricated products, and general knowledge of plastics.

Important is the SPI's Plastics Learning Network (PLN) televised training program for plastic production workers. It prepares people for the SPI National Certification in Plastics examination. Though mechanisms for distribution vary, state funding for SPI training and certification started to provide training for plastic workers in New York, North Carolina, South Carolina, Pennsylvania, Florida, and Kentucky. Contact SPI, tel: 202-974-5246; e-mail gmoore@socplas.org for details.

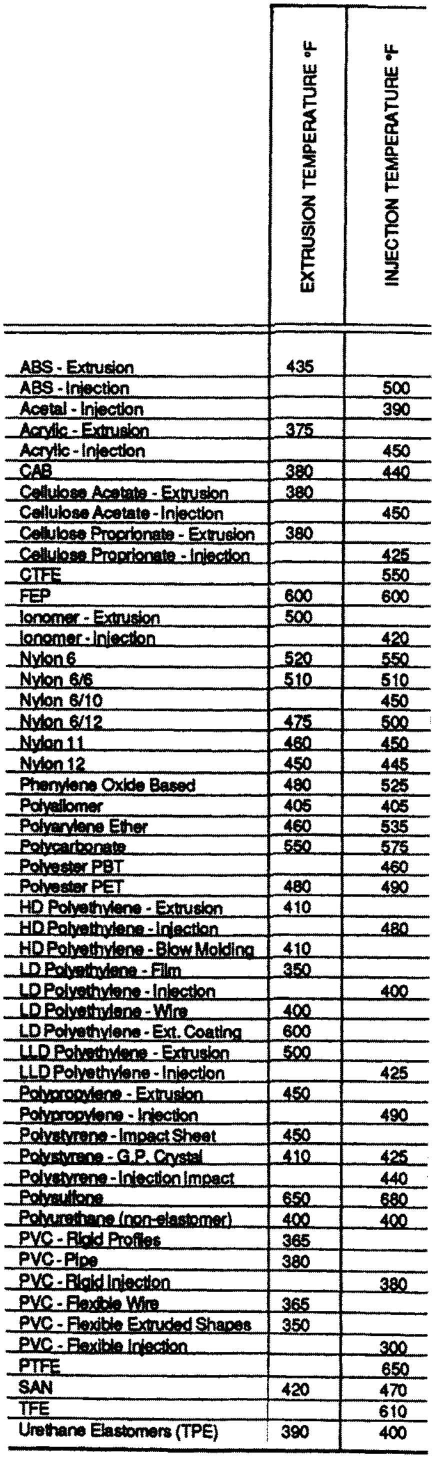
Processing fundamental

While the processes differ, there are elements common to many of them. In the majority of cases, TP are melted by heat so they can flow. Pressure is often involved in forcing the molten plastic into a mold cavity or through a die and cooling must be provided to allow the molten plastic to harden. With TSs, heat and pressure also are most often used, only in this case, higher heat (rather than cooling serves to cure or harden the TS plastic usually under pressure in a mold cavity. The descriptions of processes that follow this chapter cover the basics of the major fabricating systems. It should be recognized, however, that there are variations in virtually every process in order to service a particular market or servicing a particular plastic that represents some degree of deviation from the basics.

An important factor for the processor is obtaining the best processing temperature for the plastics used. A guide is obtained from past experience and/or the material producer (Table 3.3). The plastics with or without extensive additives, fillers, and/or reinforcements influence the temperature setting. The crystalline and amorphous thermoplastics have different melt temperature requirements that influence properties such as mechanical (Chapter 1). This type of information on initial start-up of the fabricating equipment is important but only provides a guide. The set-up person determines the best conditions (usually requires certain temperature, pressure, and time profiles) for the plastic being processed. Recognize that if the same plastic is used with a different machine (with identical operating specifications) the probability is that new control settings will be required. Reason is that, like the material, machines have variables (Chapter 1).

Understand and measuring melt flow or heat behavior of plastics during processing is important.[487] It provides a means for determining whether a plastic can be fabricated into a useful product such as a usable extruded extrudate, completely fill a mold cavity, provide mixing action in a screw plasticator, meet product thickness tolerance requirements,

Table 3.3 Examples of thermoplastic processing temperatures for extrusion and injection molding (courtesy of Spirex Corp.)



	EXTRUSION TEMPERATURE °F	INJECTION TEMPERATURE °F
ABS - Extrusion	435	
ABS - Injection		500
Acetal - Injection		390
Acrylic - Extrusion	375	
Acrylic - Injection		450
CAB	380	440
Cellulose Acetate - Extrusion	380	
Cellulose Acetate - Injection		450
Cellulose Proprionate - Extrusion	380	
Cellulose Proprionate - Injection		425
CTFE		550
FEP	600	600
Ionomer - Extrusion	500	
Ionomer - Injection		420
Nylon 6	520	550
Nylon 6/6	510	510
Nylon 6/10		450
Nylon 6/12	475	500
Nylon 11	460	450
Nylon 12	450	445
Phenylene Oxide Based	480	525
Polyallomer	405	405
Polyarylene Ether	460	535
Polycarbonate	550	575
Polyester PBT		460
Polyester PET	480	490
HD Polyethylene - Extrusion	410	
HD Polyethylene - Injection		480
HD Polyethylene - Blow Molding	410	
LD Polyethylene - Film	350	
LD Polyethylene - Injection		400
LD Polyethylene - Wire	400	
LD Polyethylene - Ext. Coating	600	
LLD Polyethylene - Extrusion	500	
LLD Polyethylene - Injection		425
Polypropylene - Extrusion	450	
Polypropylene - Injection		490
Polystyrene - Impact Sheet	450	
Polystyrene - G.P. Crystal	410	425
Polystyrene - Injection Impact		440
Polysulfone	650	680
Polyurethane (non-elastomer)	400	400
PVC - Rigid Profiles	365	
PVC - Pipe	380	
PVC - Rigid Injection		380
PVC - Flexible Wire	365	
PVC - Flexible Extruded Shapes	350	
PVC - Flexible Injection		300
PTFE		650
SAN	420	470
TFE		610
Urethane Elastomers (TPE)	390	400

etc. The melt flow is an indication of whether its final properties will be consistent with those required by the product. Subjects such as rheology, molecular weight distribution (MWD), viscosity, and thermodynamics are involved when discussing melt flow (Chapter 1).

Melt Flow Analysis
Measuring melt flow is important for two reasons. First, it provides a means for determining whether a plastic can be formed into a useful product such as completely fill a mold cavity, a usable extruded extrudate, provide mixing action in a screw, meet product thickness requirements, etc. Second, the flow is an indication of whether its final properties will be consistent with those required by the product. The target is to provide the necessary homogeneous melt during processing to have the melt operate completely stable and working in equilibrium.

In practice, even though with the developments that have occurred in the past and continue, this perfect stable situation is never achieved and there are variables that affect the output. If the process is analyzed one can decide that two types of variables affect the quality and output rate. They can be identified as: (1) the variables of the machine's design and manufacture and (2) the operating or dynamic variables which control how the machine is run.

Software provides simulation of the desired process and comparison with reality.[487] By applying flow analysis one gains a comprehensive understanding of the melt flow-filling process based on process controls. The most sophisticated computer models provide detailed information concerning the influence of filling conditions on the distribution of flow patterns as well as flow vectors, shear stresses, frozen skin, temperatures and pressures, and other variables. The less sophisticated programs that model fewer variables are also available. From these data, conclusions regarding tolerances, as well as part quality in terms of factors such as strength and appearance, can be drawn. Location of weld lines and weld line integrity can be predicted. The likelihood warping surfaces, blemishes, and strength reductions due to high-shear stress, can be anticipated. On this basis, the best filling conditions can be selected. An example of this software is from Spirex Corp. called The Molder's Technician.

Melting Temperature
Also called melting point. It is the melt temperature (T_m) at which a plastic liquefies on heating or solidifies on cooling. T_m depends on the processing pressure and time at heat, particularly during a slow temperature change for relatively thick melts. Also if T_m is too low, the melt's viscosity is high so that more power is required to process the

plastic. Degradation can occur if the viscosity is too high. Some plastics have a melting range rather than a single point. Amorphous plastics do not have melting points, but rather a softening range and undergo only small volume changes when solidified from a melt, or when the solid softens and becomes a fluid. They start melting as soon as the heat cycle begins. It is often taken at the peak of the DSC (differential scanning calorimeter) thermal analysis test equipment.[3, 4] Crystalline plastics have considerable order of the molecules in the solid state, indicating that many of the atoms are regularly spaced. They have a true melting point with a latent heat of fusion associated with the melting and freezing process, and a relatively large volume change during fabrication; the transition from melt to solid.

Newtonian Melt Flow Behavior
It is a flow characteristic where a material flow immediately on application of force and for which the rate of flow is directly proportional to the force applied. It is a flow characteristic evidenced by viscosity that is independent of shear stress to strain rate.[1] Water and thin mineral oils are examples of Newtonian flow.

Non-Newtonian Melt Flow Behavior
It is a flow characteristic where a material has basically abnormal flow response when force is applied. That is, their viscosity is dependent on the rate of shear. They do not have a straight proportional behavior with application of force and rate of flow (Figure 3.1). When proportional, the behavior has a Newtonian flow.

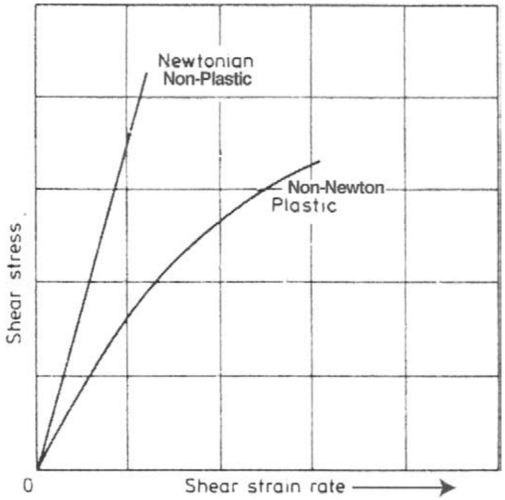


Figure 3.1 Non-plastic (Newtonian) and plastic (non-Newtonian) melt flow behavior (courtesy of Plastics FALLO)

Melt Flow Deviation

The characteristic of the deviation from the ideal behavior may be of several different types. One type called apparent viscosity may not be independent of the rate of shear; it may increase with shear rate (shear thickening or shear dilatancy) or decrease with rate of shear (shear thinning or pseudoplasticity). The latter behavior is usually found with plastic melts and solutions. In general such a dependency of shear stress on shear rate can be expressed as a power law. Another type is where the viscosity may be time dependent, as for material exhibiting thixotropic behavior. [Thixotropic is a characteristic of material undergoing flow deformation where viscosity increases drastically when the force inducing the flow is removed. In respect to materials, gel-like at rest but fluid or liquefied when agitated (such as during molding). Having high static shear strength and low dynamic shear strength at the same time. Losing viscosity under stress.]

Melt Flow Rate

MFR tests are used to detect degradation in fabricated products where comparisons, as an example, are made of the MFR of pellets to the MFR of product.[3, 143] MFR has a reciprocal relationship to melt viscosity. This relationship of MW (molecular weight) to MFR is an inverse one; as the MFR increases, the MW drops. MW and melt viscosity is also related; as one increases the other increases.

Melt Flow Performance

In any practical deformation there is local stress concentrations. Should the viscosity increase with stress, the deformation at the stress concentration will be less rapid than in the surrounding material. The stress concentration will be smooth and the deformation stable. However, when the viscosity decreases with increased stress, any stress concentration will cause catastrophic failure (Figure 3.2).

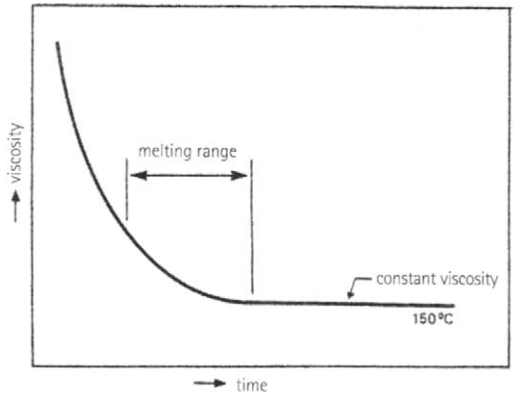


Figure 3.2 Relationship of viscosity to time at constant temperature

Melt Flow Defect

Flow defects, especially as they affect the appearance of a product, play an important role in many processes. Defects can be identified and corrected.[3, 143] These flow analyses can be related to other processes and even to the rather complex flow of injection molding.

Melt Index

MI test (extrusion plastometer) is the most widely used rheological device for examining and studying the behavior of TPs in many different fabricating processes. It is not a true viscometer in that a reliable value of viscosity cannot be calculated from the flow index that is normally measured. However, it does measure isothermal resistance to flow, using an apparatus and test method that are standard throughout the world.[3, 143] MI is an indicator of the average molecular weight (MW) of a plastic and is also a rough indicator of processability due to molecular weight distribution (MWD) (Figure 3.3). Low MW materials have high MIs and are easy to process. High MW materials have low MIs and are more difficult to process, as they have more resistance to flow, but they are processable. End-use physical properties improve as the MI decreases. MI selection for a given application is a compromise between properties and processability.

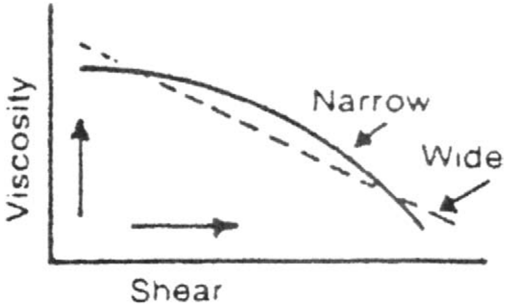


Figure 3.3 Molecular weight distribution influence on melt flow

Inline Melt Analysis

There are systems that provide real-time online evaluation of mixing and melt quality. An example is that of the Spirex Technical Center (Youngstown, OH 44513) system. This system is exclusively used in the Technical Center with the Johnson Extruder. The University of Paderborn in Paderborn, Germany initially developed this system. It system uses a custom die with quartz window, a DC light source and a special video camera to measure light intensity passing through the melt flow. This light intensity is affected by the efficiency of a screw to disperse a standardized plastic/color concentrate mix. The computer software collects data during a test run and calculates a standard deviation. The lower the standard deviation, the better the mixing; the higher the standard deviation, the poorer the mixing.[144] With the use of this sophisticated system, actual levels of mixing quality can be measured. Spirex can now evaluate all of their patented mixing elements along with many of the other mixing elements that are available to the plastics industry today.

Thermodynamic

Basically thermodynamics is the scientific principle that deals with the inter-conversion of heat and other forms of energy. Thermodynamics (thermo = heat + dynamic = changes) is the study of these energy heat transfers. The law of conservation of energy is called the first law of thermodynamics. This first law is the energy that can be converted from one form to another but it cannot be created or destroyed. The second law is the entropy of the universe increases in a spontaneous process and remains unchanged in a reversible process. It can never decrease. In turn entropy is a measure of the unavailable energy in a thermodynamic system, commonly expressed in terms of its exchanges on an arbitrary scale with the entropy of water at 0C (32F) being zero. The increase in entropy of a body is equal to the amount of heat absorbed divided by the absolute temperature of the body.

With the heat exchange that occurs during processing, thermodynamics becomes important. It is the high heat content of melts (about 100 cal/g) combined with the low rate of thermal diffusion (10^{-3} cm^2/s) that limits the cycle time of many processes. Also important are density changes, which for crystalline plastics may exceed 25% as melts cool. Melts are highly compressible; a 10% volume change for a force of 700 kg/cm^2 (10,000 psi) is typical. A surface tension of about 20 g/cm may be typical for film and fiber processing when there is a large surface-to-volume ratio.

Thermodynamic properties provide a means of working out the flow of energy from one system to another. Any substance of specified chemical composition perpetually in electrical, magnetic, and gravitational fields, have six fundamental thermodynamic properties, namely pressure, temperature, volume, internal energy, entropy, and enthalpy. All changes in these properties must fulfill the requirements of the first and second law of thermodynamics. The third law provides a reference point, the absolute zero temperature, for all these properties although such a reference state is unattainable. The proper modes of applying these laws to the above five fundamental properties of an isolated system constitute the well-established subject of thermodynamics.

Thermodynamic Phase Transformation
In thermodynamic equilibrium a system may be composed of one or several physically distinct macroscopic homogeneous parts called phases, which are separated from one another by well-defined interfaces. These phases are determined by several parameters such as temperature, pressure, and electric and magnetic fields. By continuously varying the parameters it is possible to induce the transformation of the system from one phase to another.

Thermodynamic and Statistics
This discipline tries to compute macroscopic properties of materials from more basic structures of matter. These properties are not necessarily static properties as in conventional mechanics. The problems in statistical thermodynamics fall into two categories. First it involves the study of the structure of phenomenological frameworks and the interrelations among observable macroscopic quantities.

The secondary category involves the calculations of the actual values of phenomenology parameters such as viscosity or phase transition temperatures from more microscopic parameters. With this technique, understanding general relations requires only a model specified by fairly broad and abstract conditions. Realistically detailed models are not needed to understand general properties of a class of materials. Understanding more specific relations requires microscopically detailed models.

Machines not alike

Just like people, not all machines are created equal. Recognize that identical machine models, including auxiliary equipment, built and delivered with consecutive serial numbers to the same site can perform so differently as to make some products completely unacceptable by the customer even when they were installed properly.

Plastic processing performance

This review provides an introduction to processing performances; many more examples are provided throughout this book. The plastic melt flow patterns resulting from the conditions of a particular fabricating process are very important in affecting product performances. As the temperature increases the plastic goes through the phases of glassy, transition, rubbery, to melt flow. The melting of plastics follows different phases that effect performances.[487]

Reinforcing fibers, specifically the glass fibers are brittle. When they are used in conjunction with a brittle matrix, as are certain TSs, it might be expected that the plastic composite would have low fracture energy. This is not true, and the impact strength of most glass-TS reinforced plastics is many times greater than the impact strengths of either the fibers or the matrix. Impact strength is higher if the bond between the glass fibers and the matrix is relatively weak, because if it is so strong that it cannot be broken, cracks will propagate across the matrix and fibers, and very little energy will be absorbed. Thus, there is a conflict between the requirements for maximum tensile or flexural modulus or strength (long glass fibers and strong interface bonds) and maximum impact strength (Chapter 15). [1, 4, 427]

To predict product dimensions and the fluctuation of dimensions (tolerances) during a production run, many variables have to be considered. These include the plastic materials with their variabilities (Chapter 1), geometry of the product that includes thicknesses, toolmaking quality applied in producing the mold/die, and very important the processing conditions and fluctuations inherent during processing. Computer programs developed have made it possible to provide model guides that tend to understand the complex (controllable) interactions of these many factors. This allows fabricators to more accurately predict product dimensions and to model the relationship between the control of the molding process and the product tolerances.

This interplay of the many variables is extremely complex and involves a matrix of the many variables. As an example in the molding simulation TMconcept system programmed Molding and Cost Optimization (MCO) of Plastics & Computer Inc., Dallas, TX, there are well over 300 variables.[145] It is not reasonable to expect a person using manual methods to calculate these complex interactions even if molding only a modest shaped product without omissions or errors. Computerized process simulation is a practical tool to monitor the influence of design alternatives on the processability of the product and to select molding conditions that ensure the required product quality.

Process used provides different control capabilities. As an example closed molding (injection, compression, etc.) provides fine detail on all surfaces. Open molding (blow molding, thermoforming, spray-up, etc.) provides detail only on the one side in contact with the mold, leaving the second side free-formed. Continuous production (extrusion and pultrusion) yields products of continuous length. Hollow (rotational or blow) produces hollow products. These processes can be used creatively to make different types of products. For example, two molded or thermoformed components can be bonded together to form a hollow product or they can be blow molded (Chapters 6 & 7).

Plastic Memory

Fabricated TPs can be bent, pulled, or squeezed into various useful formed shapes. But eventually when heat is added, they return to their original form. This behavior can be annoying or provide interesting design possibilities for all types of fabricated products. When the change is unwanted it is called creep; when the change is skillfully adapted to use in the overall design, it is referred to as plastic memory.

Practically all materials (metals, etc.) when bent, stretched, or compressed alter their molecular structure or grain orientation to accommodate the deformation permanently. With TPs they temporarily assume the deformed shape and always maintain the internal stresses that want to force the material back to its original shape. After forming the shapes heat can be applied so that they return to their original shapes. An example of applying this plastic memory behavior is to use stretched film around the mating section of two tubes. With heat applied the film shrinks and produces a tight grip where the tubes meet. Other examples are flat communication cable wraps, heat-shrinkable furniture webbings, pipe fittings, medical devices, and many other products

This behavior results from stress relaxation and other viscoelastic phenomena that are typical of TPs. In addition to using heat TPs such as polyolefins, neoprenes, silicones, and other cross-linkable TPs are example of plastics that can be given memory either by radiation or by chemically curing. Fluoroplastics need no such curing. When this phenomenon of memory is applied to fluoroplastics such as TFE, FEP, ETFE, ECTFE, CTFE, and PVF, interesting and useful high-temperature or wear-resistant applications become possible.

Orientation

The process of plastic orientation consists of a controlled system for stretching TP molecules in unioriented [unidirectional (UD)] or bioriented [biaxial direction (BD)]. Orientation in effect provides a means of tailoring and improving the properties of plastics such as increasing strength, stiffness, toughness; optics, electrical, and/or other properties. Also gained is resistance to liquid and gas permeation, crazing, microcrack, and others in the direction or plane of the orientation. Overall the usual result is that improved product performance-to-cost occurs.

A TP's molecular orientation can be accidental or deliberate. Accident can occur during the processing where unwanted excessive frozen-in stresses develop, however with the usual proper process control, there is no accidental orientation. The frozen-in stresses with certain TPs can be extremely damaging with products being subjected to environmental stress cracking or crazing in the presence of heat, chemicals, etc.

During processing (extrusion, injection, blow molding, etc.) the molecules tend to be more oriented than relaxed, particularly when the melt is subjected to excessive shearing action. After temperature-time-pressure is applied and the melt goes through restrictions (mold, die, etc.), the molecules tend to be stretched and aligned in a parallel form. The result can be undesirable changes in the different directional properties and dimensions immediately when processed and/or thereafter when in use if stress relaxation occurs.

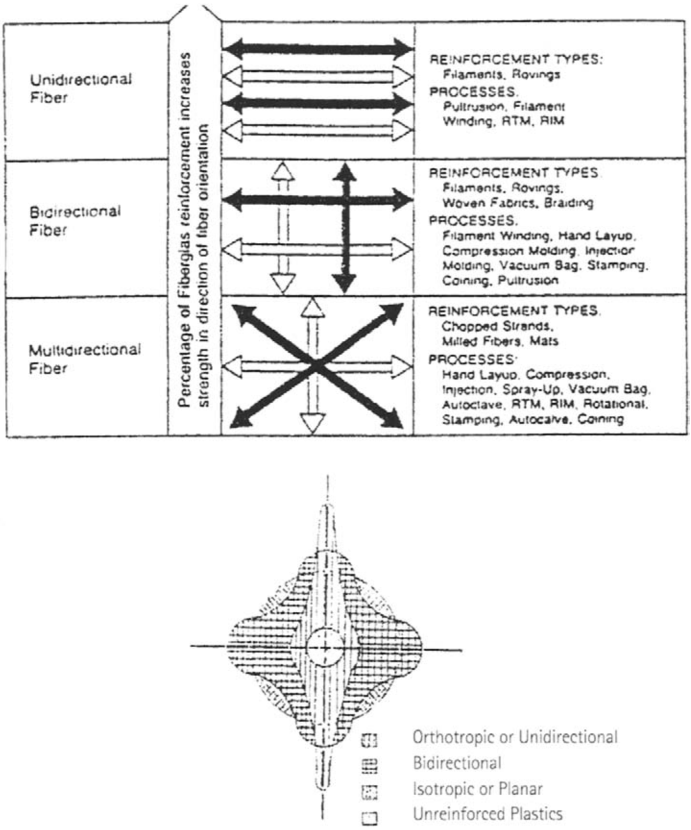
By deliberate stretching, the molecular chains of a plastic are drawn in the direction of the stretching, and inherent strengths of the chains are more nearly realized than they are in their naturally relaxed configurations. Stretching can take place with heat during or after processing by blow molding, extruding film, thermoforming, etc. Products can be drawn in one direction or in two opposite directions, in which case many properties significantly increase uniaxially or biaxially.

The amount of change depends on the type of TP, the amount of stretching, and, most important, its rate of cooling. The faster the rate, the more retention there is of the frozen orientation. After processing, products could be subject to stress relaxation, with changes in performance and dimensions. With certain plastics and processes there is an insignificant change. If changes are significant and undesirable, one must take action to change the processing conditions during and/or after processing. As an example during processing increase the cooling rate. Annealing of the product is an after processing condition approach.

Practically all TPs can undergo orientation, although certain types find it particularly advantageous such as PET, PP, PVC, PE, PS, PVDC, PVA, and PC. The largest market for plastics worldwide, consuming about 20wt% of total, is oriented plastic film. Stretching can take place in-line or off-line with or without tenter frames (stretching frames) using the appropriate temperature-pull rates. During extrusion of flat individual or multiple layers of different plastic films or sheets can be performed in-line. Off-line tenter frames are predominantly used. Details on orientation are provided in Chapter 5 and other chapters.

Reinforced Directional Property

An important type of orienting fabricated products concerns applying directional properties to plastics by using fiber reinforcements. Orientation is the alignment of fiber reinforcement within the product that affects mechanical properties. The reinforced plastic (RP) properties increase in the direction of alignment (Figure 3.4).


Percentage of Fiberglas reinforcement increases strength in direction of fiber orientation
Orthotropic or Unidirectional
Bidirectional
Isotropic or Planar
Unreinforced Plastics

Unidirectional Fiber	REINFORCEMENT TYPES: Filaments, Rovings PROCESSES. Pultrusion, Filament Winding, RTM, RIM
Bidirectional Fiber	REINFORCEMENT TYPES. Filaments, Rovings. Woven Fabrics, Braiding PROCESSES. Filament Winding, Hand Layup, Compression Molding, Injection Molding, Vacuum Bag, Stamping, Coining, Pultrusion
Multidirectional Fiber	REINFORCEMENT TYPES. Chopped Strands, Milled Fibers, Mats PROCESSES: Hand Layup, Compression, Injection, Spray-Up, Vacuum Bag, Autoclave, RTM, RIM, Rotational, Stamping, Autocalve, Coining

Figure 3.4 Examples of reinforced plastic directional properties

In an RP construction both plastics and fibers influence orientation properties. For example, with certain TPs, the plastic's molecular orientation can be used to aid in increasing stiffness, strength, toughness, as well as craze and microcrack resistance in the direction of the plane or the plane of orientation. By far the main source of orientation is with fibers that cause positive and significant increased performance.

Such effects are obvious in continuous filament winding (Chapter 15). Not so obvious are the anisotropic materials properties resulting from many TP processes. For example, viscous melt flow of hot plastic into injection molds produces an oriented structure (Chapter 4), usually having greater strength with crystalline TPs in the direction of flow than perpendicular to this direction. Shrinkage also is usually greatest with crystalline TPs perpendicular to the direction of flow. With amorphous TPs, greatest shrinkage can be in the direction of flow; however as in IM, melt flow control can readily have even shrinkage in all directions. With fibers, shrinkage is less than unreinforced RPs (URPs) in the flow and perpendicular directions.

Plastic Deformation

Plastics have certain degrees of elasticity associated with them. As an example if the plastic stretches within its elastic limit, it will eventually return to its natural shape. When overstressed, it reaches what is known as plastic deformation, meaning the plastic will not return to its original shape.

This behavior can effect processability. It is important to keep the drag force from melt feed mechanism friction as low as possible and to keep acceleration of the feed material low enough so the product does not permanently deform or tear.

Sinusoidal acceleration profiles reduce the load on the plastic by providing gentle forces near zero speed and top speed while making up for lost ground in the middle with the result of diminishing stretching. Stretching also contributes to reduced dimensional accuracy. This situation can be overcome by either compensating for the stretch in the process controller when the amount of stretch is predictable or by installing a position verification device between the feed mechanism and the post-feed process.

Coextrusion/Coinjection: Fabricating Multilayer

Multilayer fabrication is the simultaneous processing of two to up to at least seven plastics melt streams meeting in a die/mold to produce laminated or multilayer plastic products. Product performances gained are a combination of what each individual plastic provides with a potential of obtaining synergistic gains. Each ply of the laminated structure imparts a desired property such as impermeability or barrier/

resistance to some environment, heat stability, toughness, tear resistance, lower cost, and so on.

The lay-up can include recycled material and/or a low cost material that will reinforce more expensive material(s) strengthwise, tear resistance, and so on. It produces products (such as extruded film, sheet, cable covering, and pipe; also coinjection bottles, containers, thermoformed packages, etc.) where two or more different or similar plastics go through a single die/mold. Two or more orifices from each extruder or each injection molding machine processing the different plastics are arranged so that the extrudates merge and "weld" together into a single structure prior to cooling (Chapters 4, 5, 6, 17).

When no bonding layers occur in a plastic laminated composite structure, a plastic tie-layer is used that provides bonding. Choosing the proper adhesive layer is by no means a simple task since evaluation includes processability, bonding capabilities, and performance in the final product. There are many different types with different capabilities, with EVOHs being one of the important ones.

When thicker wall thickness can be used low density foam core products are produced such as in pipe and paneling. This multilayer sandwich structure provides reduced material costs without sacrificing performance, in fact properties can be improved by using the sandwich design advantages.[1]

Certain melt processing factors have to be considered in order to eliminate problems. Some of these factors can be compensated by the available plasticator and die/mold adjustments. An unsteady balance of shear forces causes the interfacial instability. Examples of the factors include:

1. different melt temperatures of adjacent layers;
2. plastic viscosity differentials that should not be greater than 2 to 4/1; and
3. minimum thickness of a cap (top) layer because it is subjected to a high shear stress is usually limited to 5 to 10% of the total thickness.

There is a tendency for the less viscous plastic to migrate to the region of high shear stress in the flow channel causing an interface deformation. With a great difference in viscosities existing between adjoining layers, the less viscous tends to surround or encapsulate the other plastic. Result could be fuzzy interfaces, orange peel, etc.

When running a line, make provisions to adequately alarm the operator if one of the plasticators trips out. This will prevent melt from back flowing into the stopped machine and creating a blockage in the feed section that could become hazardous.

Plasticator melting operation

The major processing methods that process well over 80wt% of all plastics are extrusion, injection molding, and blow molding. These processes as well as a few others use a plasticator to melt plastics. It is a very important component in a melting process with its usual barrel and screw. If factors such as the proper screw design and/or barrel heat profile are not used correctly fabricated products may not meet or maximize their performance and very important not provide for low cost process.

Plasticators have a wide operating range to meet different performance requirements of all the different plastics processed. Its rotating drive system can be via a hydraulic and/or electrical motor. Electrical motors tend to increase melt processing efficiency that in turn increases production rate. They have a wide operating range to meet different performance requirements of all the different plastics processed. Important is to obtain maximum throughput with as close to a perfect melt quality. Since the start of using screw plasticators and with time passing definite improvements have been occurring in the melt quality. This action continues because advancements tend to be endless in applying advanced screw designs and the changing melting characteristics of plastic materials.

Screw

The primary purpose for using a screw is to take advantage of its mixing action. Theoretically speaking, the motion of the screw should keep any difference in melt temperature to a minimum. It should also permit materials and colors to be blended better with the result that a more uniform melt is delivered to the mold or die. Figures 3.5 to 3.8 provide an introduction to the performance of a plasticator where the screw usually has a 17.6 degree flight helical angle.

Figure 3.5 identifies the following three main zones of a screw:

Feed Zone: This is the part of the screw that picks up the plastic at the feed opening (throat) plus an additional portion downstream. Many screws, particularly for extruders, have an initial constant lead and depth section, all of which is considered the feed section. This section can be welded onto the barrel or a separate part bolted onto the upstream end of the barrel. The feed section is usually jacked for fluid heating and/or cooling.

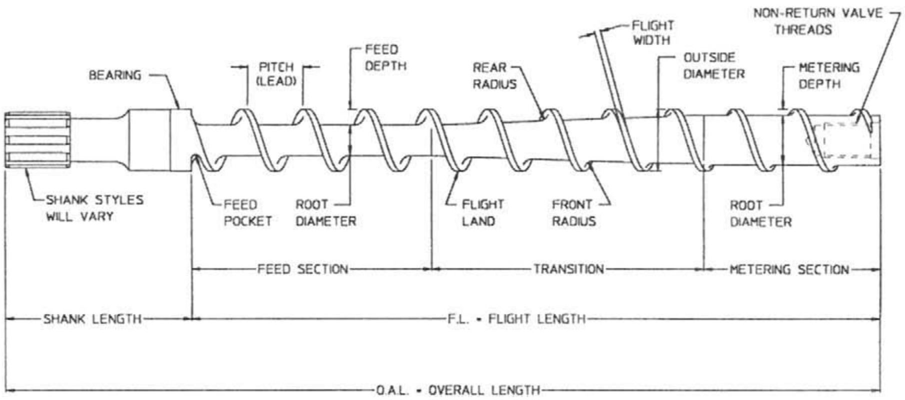
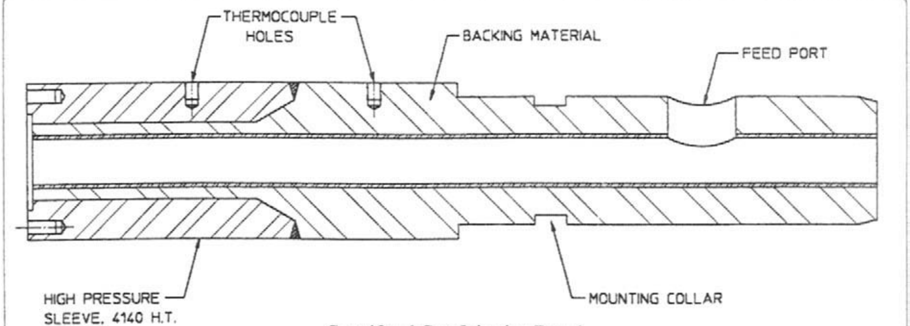
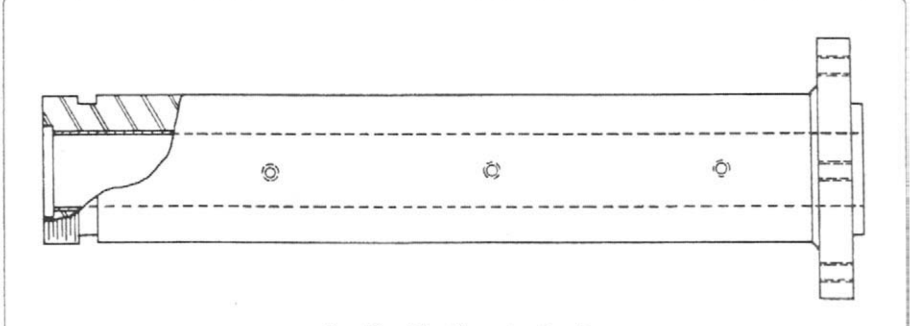

NON-RETURN VALVE THREADS
FLIGHT WIDTH
FEED DEPTH
OUTSIDE DIAMETER
PITCH (LEAD)
REAR RADIUS
METERING DEPTH
BEARING
SHANK STYLES WILL VARY
FEED POCKET
ROOT DIAMETER
FLIGHT LAND
FRONT RADIUS
ROOT DIAMETER
FEED SECTION
TRANSITION
METERING SECTION
SHANK LENGTH
F.L. = FLIGHT LENGTH
O.A.L. = OVERALL LENGTH

Figure 3.5 Nomenclature of an injection screw (top) and extrusion screw (courtesy of Spirex Corp.)


THERMOCOUPLE HOLES
BACKING MATERIAL
FEED PORT
HIGH PRESSURE SLEEVE, 4140 H.T.
MOUNTING COLLAR

Centrifugal Cast Injection Barrel



Centrifugal Cast Extrusion Barrel

Figure 3.6 Nomenclature of an injection barrel (top) and extrusion barrel (courtesy of Spirex Corp.)

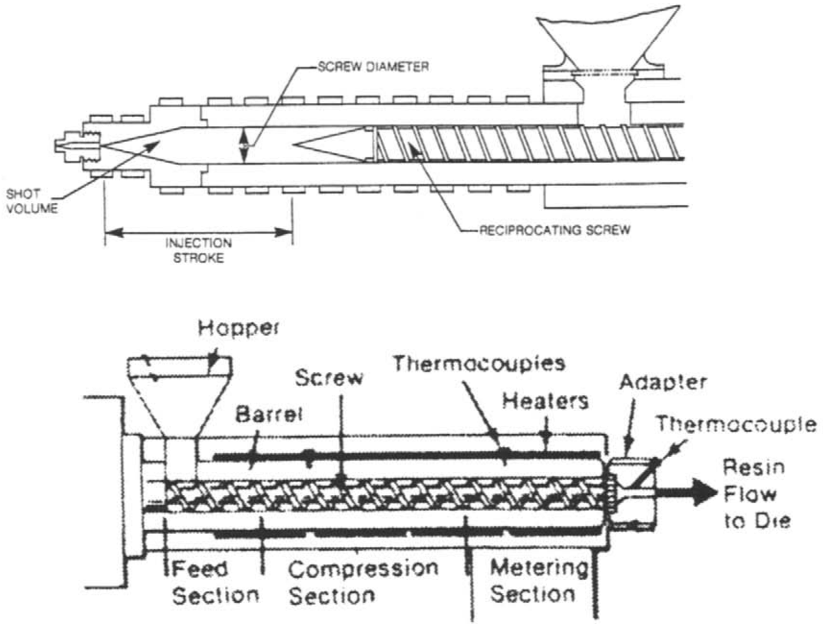

SCREW DIAMETER
SHOT VOLUME
INJECTION STROKE
RECIPROCATING SCREW
Hopper
Screw
Thermocouples
Adapter
Heaters
Barrel
Thermocouple
Resin Flow to Die
Feed Section
Compression Section
Metering Section

Figure 3.7 Assembled screw-barrel plasticator for injection molding (top) and extruding. (courtesy of Plastics FALLO)

Transition Zone: It is the section, also called the compression zone, of a screw between the feed zone and metering zone in which the flight depth decreases in the direction of discharge. In this zone the plastics starts in both solid and molten state with target to have all molten upon leaving this zone.

Metering Zone: This section is a relatively shallow portion of the screw at the discharge end with a constant depth and lead usually having the melt moves 3 or 4 runs of the flight length.

Many different screw designs are available to meet the desired performance for the different plastics being processed. The features common to all screw plasticators are screw(s) with matching barrel(s) that have at least one hopper/feeder in-take entrance for plastics, and one discharge port/exiting of the melt. The essential factor in their pumping process is the interaction between the rotating flights of the screw and the stationary barrel wall. If the plastic is to be mixed and conveyed at all, its friction must be low at the screw surface but high at the barrel wall. If this basic criterion is not met the material may rotate with the screw without moving at all in the axial direction and out through the die/mold. The clearance between the screw and barrel is usually extremely small.

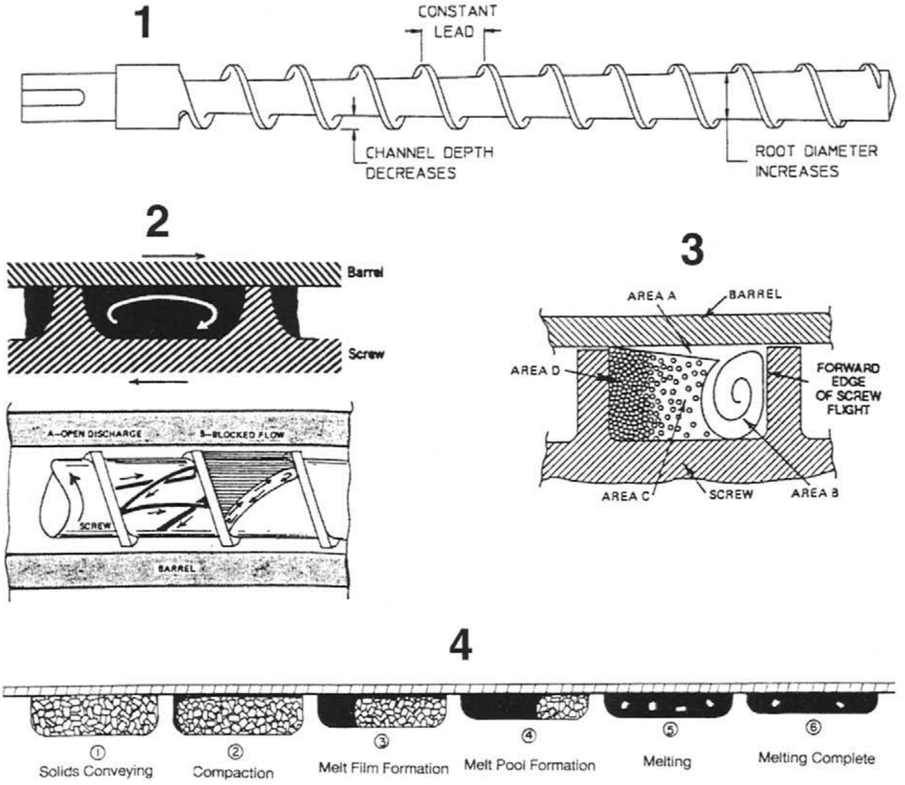

1
CONSTANT LEAD
CHANNEL DEPTH DECREASES
ROOT DIAMETER INCREASES
2
Barrel
Screw
A—OPEN DISCHARGE
B—BLOCKED FLOW
SCREW
BARREL
3
AREA A
BARREL
AREA D
FORWARD EDGE OF SCREW FLIGHT
AREA C
SCREW
AREA B
4
① Solids Conveying
② Compaction
③ Melt Film Formation
④ Melt Pool Formation
⑤ Melting
⑥ Melting Complete

Figure 3.8 Action of plastic in a screw channel during its rotation in a fixed barrel: (1) highlights the channel where the plastic travels; (2) basic plastic drag actions; and (3) example of melting action as the plastic travels through the barrel where areas A and B has the melt occurring from the barrel surface to the forward screw surface, area C has the melt developing from the solid plastic; and area D is solid plastic; and (4) melt model of a single screw (courtesy of Spirex Corp.)

In the output zone, both screw and barrel surfaces are usually covered with the melt, and external forces between the melt and the screw-channel walls has no influence except when processing extremely high viscosity materials such as rigid PVC (polyvinyl chloride) and UHMWPE (ultra high molecular weight polyethylene). The flow of the melt in the output section is affected by the coefficient of internal friction (viscosity) particularly when the die/mold offers a high resistance to the flow of the melt. The constantly turning screw augers the plastic through the heated barrel where it is heated to a proper temperature profile and blended into a homogeneous melt. The rotation causes forward transport. It is the major contributor to heating the plastic via the plastic's shearing action once the initial barrel heat startup occurs. The melting action through the screw is shown in Figure 3.8.

The design of the screw is important for obtaining the desired mixing and melt properties as well as output rate and temperature tolerance on melt. Generally most machines use a single, constant-pitch, metering-type screw for handling the majority of plastic materials. Most of the energy that a screw imparts to the plastic material is by means of shear. The velocity of the plastic relates to the shearing action between two surfaces moving in relation to each other. These surfaces are the barrel ID and the root diameter of the screw.

Until the 1960s TSs (thermosets) were primarily molded using compression or transfer presses (Chapter 14). At that time screw injection machines with modifications were developed to process TSs. These modifications included: low to zero compression for screw depths, deeper channel depths, short length to diameter screws (L/Ds), tool steel construction, barrel cooling with heat transfer fluids, and spiral down discharge ends in place of non-return valves.[3]

Feeding Problem

Generally, the plastic being fed flows by gravity (usually controlled weightwise) from the feed hopper down into the throat of the plasticator barrel. Special measures are taken and devices used for plastics that do not flow easily or can cause hang-ups (bridging or solidification resulting in plastic not flowing through the hopper).[3, 143] This initial action is where the plastic is in a solid state with its temperature below its melting point. As the screw turns in the heated barrel, plastic falls down into its channel. Frictional forces develop in the plastic during plasticizing so that the melt moves forward toward the mold/die.

The action that pushes solid particles forward in the feed section of a single screw extruder, blow, or injection machine has always been a potential for one of the weakest features of these machines. This forward feeding force near the feed hopper is often weak and erratic and is classified as non-positive. It can be so tenuous that a specific screw/barrel combination will feed virgin but little or no additions of regrind, or one feedstock shape but not another, and often one family of plastics but not another. This action results in non-uniform feed that will in turn result in poor production rates, non-uniform output (surging), and poor product quality.[147]

Feeding mechanism of solid plastics is dependent on the surface friction of the screw surfaces and the inner surface of the barrel. The easier the solid particles of plastic slide on the screw, the better the screw will feed. Also, the greater the friction or resistance to sliding on the barrel wall, the better it will feed. This is perhaps best visualized by considering the worst condition where it slides on the barrel and literally sticks to the screw. In this case, the plastic will merely go round and round with the screw and never move forward along the barrel. Processors have several medium time and medium cost solutions that may help. It is possible that a redesign of the screw by machining or replacement will cure the problem for a specific situation. It is also possible that the surface of the feed section of the screw can be altered to decrease friction. Vapor honed or other release finishes of chromed surfaces can help.

The most immediate tool available to the processor is finding the optimum barrel temperature settings. This optimum setting will give the best feeding temperature at the inside of the barrel for that RPM and plastic combination. These feed critical settings are the rear ones and will vary depending on many things, including RPM, barrel wall thickness, depth of thermocouple recording melt temperature, plastic composition (filler, etc./Chapter 1), and other factors. The intent is to obtain an inside barrel wall temperature that will be hot enough to provide a viscous sticky melt film early without overheating to make the plastic too fluid so that it flows easily.

Sometimes these temperature settings can cure a problem, however based on experience from different sources looking for the right settings will usually report a low probability of success. An important consideration in all of these feed problems is that many are improperly diagnosed and are actually melting problems. Every screw design and plastic combination has a practical limit for the rate at which it can melt the material. If the screw is run at an RPM that exceeds the ability of the screw to melt material at that rate, solids blocks will form with surging and the appearance of poor feeding. This is particularly true of plastics with high specific heats such as the polyolefins. If you obtain low and erratic output in conjunction with temperature override in the transition, the problem is usually melting not feed.

Screw/Barrel Bridging

When an empty hopper is not the cause of machine output failure, plastic might have stopped flowing through the feed throat because of screw bridging. An overheated feed throat, or startup followed with a long plasticator operating delay, could build up sticky plastics and stop flow in the hopper throat. Plastics can also stick to the screw at the feed throat or just forward from it. When this happens, plastic just turns around with the screw, effectively sealing off the screw channel from moving plastic forward. As a result, the screw is said to be bridged and stops feeding the screw. The common solution is to use a proper rod such as brass rod to break up the sticky plastic or to push it down through the hopper without damaging the machine.

Multi-Stage Screw

A variation of the metering screw is the two-stage, also called multi-screw or double metering screw. It basically is two single-stage screws attached to each other. There are also three-stage screws. The two-stage screw was first designed to run with a vented extruder. In an extruder, the plastic is melted and pumped by the first stage into the vent or second feed section. In the deep vent section, the plastic melt is decompressed and the entrapped volatiles (moisture, etc.) escape. The plastic is then compressed again and pumped by the second stage.

The two-stage screw has other advantages aside from its venting capabilities. It provides for additional mixing because of the tumbling that the plastic receives in the vent section, and because the material is compressed, decompressed, and compressed again. All of this tends to give some mixing without shear. Because the screw runs partially filled in the vent section and part of the second transition, the torque and horsepower requirements are somewhat reduced for the same output and same screw speed when compared with a single-stage screw of the same diameter and flighted length. Other advantages include fully or partially eliminating pre-drying plastic, greater use of regrind, reduced mold venting, eliminates dryer variability, compared to hopper dryers requires less space, rapid startup, and rapid color or plastic changes.

A potential problem with a two-stage screw in vented extrusion is the difficulty in balancing the first stage output. If the first stage delivers more than the second stage pumps, the result is vent flooding. If the second stage tends to take away or pump more than the first stage delivers, the result is surging of output, pressure, etc. Surging is unstable pressure build-up in an extruder leading to variable throughput and waviness in the output product's appearance. This can sometimes be adjusted by controlling the feed into the extruder or by valving the output.

Problems with one screw design arise because of changes in RPM, plastic variations, die/mold restrictions, and other variables. This is not a problem with a closed vent and a low pump ratio using a two-stage screw. The two-stage screw used in injection does not have the surging problem described above, but it is more difficult to design due to change in screw location relative to the feed and vent ports.

Drying via Venting

Melt in a plasticator must be freed of gaseous components that include moisture and air from the atmosphere and from plastics, plasticizers, and/or other additives as well as entrapped air and other gases released by certain plastics. Gas components such as moisture retention in and on plastics have always been a potential problem for all processors. All kinds of problems develop on products (splay, poor mechanical properties, dimensions, etc.). This situation is particularly important when processing hygroscopic plastics (Chapter 1). One major approach to this plastic degrading situation is by using plasticators that have vents in their barrels to release these contaminants.

It can be very difficult to remove all the gases prior to fabrication using drying equipment, from particularly contaminated powdered plastics (Chapter 1). What is required is that the melt is exposed to vacuum venting typical of most vented screws. A vacuum is connected to the vent's exhaust port in the barrel. The standard machines operate on the principle of melt degassing. The degassing is assisted by a rise in the vapor pressure of volatile constituents, which results from the high melt heat. Only the free surface layer is degassed; the rest of the plastic can release its volatile content only through diffusion. Diffusion in the non-vented screw is always time-dependent, and long residence times are not possible for melt moving through a plasticator. Thus, a vented barrel with a two- or three-stage melting screw is used.

Barrier Screw

An important development in screw design was the barrier screw. The primary reason for a barrier screw is to eliminate the problem of solids bed breakup for more efficient melting. They have been around for over a quarter century. Original developments were for extrusion, but latter they were used to solve problems in injection and blow molding. There are many different patented barrier screw designs that under the broad claims of the Geyer or Uniroyal U.S. Patent No. 3,375,549 that expired in 1985.[3, 143]

Screw Tip

Use is made of screw tip valves, popularly called non-return valve, ball check valve, or sliding ring valve. They are used in reciprocating injection and injection blow molding machines (IMM and IBMM) to control the melt flow in one direction (Chapter 4). There is also the smearhead for IMM, IBMM, and extruder. Back flow will not occur when the screw is used as a ram to push melt through the IMM nozzle and into a mold cavity. Also melt drooling from the nozzle is prevented. When valves are used they must be inspected regularly as they can easily become worn or damaged. Shut-off nozzle valves are not widely used nowadays due to material leakage and degradation, taking place within the nozzle assembly. Popular types used are the ball check and sliding ring valves. Many different valves exist with each having advantages and disadvantages based on the plastic being processed and type of IMM and IBMM to be used.

Purging

Purging is important to permit color changes, remove contaminants such as black specks, and plastic adhering to screws and barrels. At the end of a production run the plasticator may have to be cleared of all its plastics in the barrel/screw to eliminate barrel/screw corrosion (Table 3.4). This action consumes substantial nonproductive amounts of plastics, labor, and machine time. It is sometimes necessary to run hundreds of pounds of plastic to clean out the last traces of a dark color before changing to a lighter one; if a choice exists, process the light color first. Sometimes there is no choice but to pull the screw for a thorough cleaning.

Purging material include the use of certain plastics to chemical purging compounds. Popular is the use of ground/cracked cast acrylic and PE-based (typically bottle grade HDPE) plastics. Others are used for certain plastics and machines. Cast acrylic, which does not melt completely, is suitable for virtually any plastic. PE-based compounds containing abrasive and release agents have been used to purge the softer plastics such as other polyolefins, polystyrenes, and certain PVCs. These type purging agents' function by mechanically pushing and scouring residue out of the plasticator.

The chemical purging compounds are generally used when major processing problems develop. However to eliminate the major problems with their associated machinery downtimes, regularly scheduled purgings prevent quality problems and can yield operational benefits.[142, 148, 149] With the proper use of these purging agents' helps to reduce reject rates significantly. The schedule depends on factors such as plastic or plastics being processed, size and plasticator operational settings with its time schedule that it is in use. Repeated equipment shutdowns and startups are the most common cause of degraded plastic build-up. Purging compound producers can recommend the time schedule to be used in order to minimize down time and increase profits.

Table 3.4 Purging: preheat/soak time (courtesy of Spirex Corp.)

Objective

The intent of this procedure is to offer guidance in properly pre-heating and soaking the injection front-end components prior to processing.

General Thoughts

One of the best ways to avoid damage to machinery is to use purging compound during shut-down and start-up. Familiarity of this compound will be a guide for the proper soak time. Often it is acceptable to purge with a safer material, such as linear low density polyethylene (LLPE).

Do not overlook obvious sources of information. Draw on the experience of others, or records of previous jobs. The material supplier can provide recommendations from the producer. Industry contacts are a good resource of experience and other contacts. Try to compare the material to other similar materials. Exercise caution as many like-materials have different additives that result in very different properties. The soak time may change, there may be a critical temperature at which damaging gas releases, or heat sensitivity may increase.

Excessive soak time can cause a problem if the material is heat sensitive. If extra caution is necessary, a heat probe can be inserted into the nozzle, or the endcap can be removed for checking the melt directly. Once the endcap is removed, insert a temperature probe inside the non-return valve. The material within a non-return valve is generally the last to reach operating temperature. The Auto-Shut valve can be checked by using pliers to gently pull open the poppet.

Using Soak Timers

New OEM machines come with soak timers. The function of the soak timer is to lock out the injection unit until the timer times out. The timer starts once the heaters reach the operator-set temperature. Our experiences with OEM soak timers are that they are satisfactory for many materials and front-end components. However, exercise caution if you are unfamiliar with the material, or your front-end components. Our belief is that many non-return valves and materials require 40% more soak time than the OEM timer provides.

Older Machines Without Soak Timers

There are still many machines in service without soak timers. Try to compare the machine with other similar machines that do have a timer. Remember the soak time starts after the injection unit reaches the set point temperature. You know the injection unit is at set point by watching the cycling of the heater bands. Add your soak time at this point, and maintain records for your future use. Remember, you can apply the other methods stated above in *General Thoughts*.

If you do not have an adequate means to determine the appropriate soak time, there is an old industry rule-of-thumb that can help. This rule is "turn on the heaters and heat for one hour for each inch of barrel wall thickness." This rule seems to work and is actually a little on the safe side, so burning of heat-sensitive materials is a risk.

Comments on the Auto-Shut Valve

The Auto-Shut Valve requires more soak time than conventional non-return valves. This valve has a spring loaded poppet that rides in the body of the valve. There is a pool of plastic contained inside the valve by the poppet. The pool of plastic in the center of the valve, and the poppet shaft, are the last front end components to reach operating temperature. The plastic around the screw will reach operating temperature before the internals of the Auto-Shut Valve. If screw rotation occurs too soon, the plastic from the screw will flow into the valve, and either the poppet will resist opening, or the cold slug of plastic in the valve will block the flow. If the screw continues to rotate, the Auto-Shut valve may become damaged.

Barrel

The barrel, also called cylinder or pipe, is used to enclose the screw (Figure 3.6). This combination provides the control mechanism that targets to produce a uniform plasticized plastic melt of constant composition, at the required, controllable rate. To achieve this, the barrel must be made very accurately; the total out-of-alignment error, after all machining, must be less than one half of the screw/barrel clearance. The screw in the barrel provides the bearing surface where shear is imparted to the plastic material. Heating and with certain types of cooling media are housed around it to keep the melt at the desired temperature profile.

There are many options for barrel material construction with most extruder barrel designed to withstand up to at least 10,000 psi (69 MPa) internal pressures; higher pressure units [30,000 psi (210 MPa)] are manufactured for the injection molding processes since they operate at higher pressures. They have a minimum safety burst pressure of at least 50,000 psi (350 MPa). The need for corrosion and/or wear protection, cost, repair, or their combinations may determine the choice of materials. They can be made from a solid piece of metal. The most common material is carbon steel.[6]

The barrel's ID (inside diameter) with its length classifies sizes. It is common practice to refer to the L/D ratio that is the barrel length (L) to the opening diameter ratio (D). [there is also a screw length-to-diameter ratio (L/D)]. For low output, such as filament or profile extrusion 40 to 60 mm (1.6 to 2.3 in.) diameter extruders are normally used whereas for sheet 120 and 150 mm (4.7 and 5.8 in.) diameter screws are more common. Injection molding barrel diameters are approximately the same with the smaller diameters providing the smaller melt shot size to the larger diameters providing the larger melt shot size.

Downsizing machine

Very few of the installed IMMs run shot sizes anywhere near the full shot size capacity of the injection unit (Chapter 4). Typical usage is from 25 to 60%. Most suppliers of injection machines offer several sizes of injection plasticating units for any given press tonnage. The problem of having too much shot capacity can render some IMM unusable for certain plastics and applications. An example is excessive residence time for the plastic particularly the engineering materials. Any plastic that will degrade when held at injection temperatures for long periods will have problems with small shots, long cycles, and large injection units. These type plastics include PC, ABS, nylon, acetals, cellulosics, PES, and most fire-retardant grades.

Another problem associated with very large injection units and small shot sizes are relative to the plasticating screw design. In order to properly plasticize, the screw should impart approximately 40% of the energy needed to melt the plastic via the drive motor. If the screw rotation is too low and the meter zone flight depth is too deep relative to the throughput needed, very little energy will come from the screw drive. This situation will result in very poor homogenization of the melt pool that will lead to poor part quality. When the injection unit is too large, the travel of the screw needed to fill the mold is also very short, sometimes not allowing the machine drive system and electronics to be utilized effectively. A logical solution is to purchase a completely new, smaller injection unit from the original machine supplier.

Upsizing machine

To increase shot size upsizing the plasticator can be made. A number of items have to be considered for the upsizing process, such as: barrel wall thickness, resultant screw L/D, injection speed reduction, screw drive torque, and injection pressure drop. Before considering the upsizing process, one has to determine whether the output can be met properly using the decreased pressure and speeds that occur. The pressure and speeds will decrease directly proportional to the difference in the barrel ID projected areas. If this poses no problems, the L/D and structural integrity of the barrel have to be considered before proceeding.

Rebuilding vs. buying

This review is subject to pros and cons. With a logical approach the outcome depends on various factors such as extent of damage, professional feasibility to rebuild, time to be back in production, and availability of money. Even though the initial capital expenditure is much lower than for new screws and barrels (plus other equipment), the long-term economical value can be questionable. As an example machine retrofits can be tailored to meet the customer's performance requirements at 40% to 70% of a new tool. In order to provide a good basis for a decision, a technical evaluation matrix system using weighted criteria and a time related method for judging the economical value of an investment are required.

Repair

Major rebuilding and repairs involve screws and barrels. Screws and barrels are expensive and can cause downtime when damaged or worn. It may be practical (cost-effective) to repair rather than replace. It is common practice to rebuild a worn screw with hard surfacing materials (cobolt, etc.). Quite often the rebuilt screw will outlast the original screw time in service. The larger the screw, the more economical screw repairing becomes. Usually it does not pay to rebuild 50 mm (2 in.) diameter or smaller screws. To be practical as to repairing depends on the location and degree of damage.

Tooling

When processing plastics some type of tooling is required. These tools include dies, molds, mandrels, jigs, fixtures, punch dies, perforated forms, etc. for shaping and fabricating products (Chapter 17).

Process control

Overview

This is an important area that has to be thoroughly analyzed and studied to obtain the desired performance of the complete line and/or its parts such as the injection mold, extruder puller, and so on. The first task is to determine what is required and how to approach any potential problem. Adequate PC and its associated instrumentation are essential for product control. Sometimes the goal is precise adherence to a control point, other times it is sufficient to maintain a control within a comparatively narrow range. For effortless controller tuning and lowest initial and operating cost, the processor should select the simplest controller (temperature, time, pressure, flow rate, etc. that will produce the desired results. For the complete line, they can range from unsophisticated to extremely sophisticated devices that interrelate information. As an example there is the computer Hosokawa Alpine system capable of automatic startup; push a few buttons and the line is set-up in 4½ minutes.[476]

Machine control operation and the control behavior of the plastic are involved. Most important is the interaction between the machine operation and plastic behavior. Example of controls used with injection molding (a rather complex process when compared to others), extrusion, and other processes are reviewed in Chapters 4 to 16. Basically the processing pressure and temperature vs. time determine the quality of the fabricated product. The design of the control system has to take into consideration the logical sequence of all these basic functions and their ramifications. Developing a PC flow diagram requires a combination of experience (at least familiarity) of the process and a logical approach to meet the objective that has specific target performance requirements. It should be noted that none of the PC solutions address the problem of the lack of skilled setup people.

There is a continuous stream of improvements in PC. Control of machines continually enters new eras that dramatically improve ease of machine setup, allow ease of ensuring to meet fabricated product requirements, more uninterrupted operation, simplify remote handling, reduce fabricating times, cut energy costs, boast part quality, and so on.

As an example the National Research Council of Canada's Industrial Materials Institute (IMI) system uses computerized ultrasonic technology for accurate, non-intrusive, and nondestructive measurement of the surface and interior of molding materials during the filling, packing/holding, and cooling phases during injection molding. The system uses pulse-echo ultrasonic techniques similar in principle to those used for an expectant mother's sonogram to listen through tool steel and see parts as they are being molded. As an example when the ultrasonic waves meet acoustic-resistance boundary between the two different media of the mold and plastic, the air gap formed when cooling part shrinks some of the energy is transmitted through the boundary. The rest of the energy is reflected back to an ultrasonic transmitter. No mold modification is needed.

Controls cannot be considered a toy or a panacea because they demand a high level of expertise from the processor. There are those that:

1 provide closed-loop control of temperature, pressure, thickness, etc.;

2 maintain preset parameters;

3 monitor and/or correct equipment operations;

4 constantly fine tune equipment;

5 provide consistency and repeatability in the operations; and
6 self optimization of the process.

Most processes operate more efficiently when functions must occur in a desired time sequence or at prescribed intervals of time. In the past, mechanical timers and logic relays were used. Now electronic logic and timing devices are used based on computer software programmable logic controllers. They lend themselves to easy set-up, reprogramming, and provide more accurate control.

There are adaptive PCs. They are control system that changes the settings in response to changes in machine performance to bring the product back into its preset requirements or specification. The shift is maintained so that the control has adapted to changing conditions. It is a technique typically used to modify a closed loop control system. The process control comparator is the portion of the control elements that determines the feedback error on which a controller acts.

Purchasing a sophisticated PC system is not a foolproof solution that will guarantee perfect products. Solving problems requires a full understanding of their causes that may not be as obvious as they first appear. Failure to identify contributing factors when problems arise can easily result in the microprocessor not doing its job. The conventional place to start troubleshooting a problem is with the basics of temperature, time, and pressure requirement limits. Often a problem may be very subtle such as a faulty control device or an operator making random control adjustments. PC cannot usually compensate for such extraneous conditions, however they may be included in a program that provides the capability to add functions as needed.

There are two basic approaches to problem solving. Find and correct the problem applying only the control needed. Overcome the problem with an appropriate PC strategy. The approach one takes depends on the nature of the processing problem and whether enough time and money are available to correct it. PCs may in most cases provide the most economical solution. Before investigating in a more expensive system, the processor should methodically determine the exact nature of the problem to decide whether or not a better control system is available and will solve the problem. For example, the temperature differential across a mold (or die) can cause uneven thermal mold/die growth. The growth can also be influenced by uneven heat on equipment that has tiebars for platens. With injection molding the uppers can be hotter causing platens to bend where the change could be reflected on the mold operation. Perhaps all that is needed to correct the mold heat variation is to close a nearby large garage door to eliminate the flow of air upon the mold. With air conditioning all that may be required is to change its direction of airflow.

Sensor

The PC is dependent on the ability to measure parameters such as the variability of temperature, pressure, output rate, etc. are important. Sensors have traditionally played an important role in measuring and monitoring these broad ranges of parameter.[151] All sensors perform the same basic function of the conversion of one type of measurable quantity, such as temperature, into a different but equally quantifiable value, usually an electrical signal. Although the basic function remains the same, the technologies used to perform that function vary widely (Table 3.5).

Table 3.5 Guide to performance of different sensors

Type of sensor	Accuracy	Dimensional range	Transverse measurement	Reflex measurement	Freedom from interference	Material dependency	Sensor-size limitations	Complexity of equipment	Ease of calibration	Sensitivity
Rolling-contact	Good	Wide	Yes	No	Good	No	Low	Low	Easy	Med.
Air	Good	Wide	Yes	No	Good	No	Some	Med.	Easy	High
Magnetic-reluctance	Fair	To $\frac{1}{4}$"	Yes	Poss.	Fair	Some	Some	High	Easy	Med.
Sonic	Good	To 1"	Yes	Yes	Fair	Yes	Some	High	Fair	Med.
Optical	Fair	Wide	Yes	Yes	Good	Some	High	Med.	Fair	Med.
Laser-intercept	Good	Wide	Yes	Yes	Good	Some	High	Med.	Fair	High
Laser-interferometry	Exc.	Ltd.	No	Yes	Good	Yes	Some	High	Easy	High
Capacitance	Good	Med.	Yes	No	Fair	Yes	Low	High	Easy	Med.
Proximity	Good	Wide	Yes	No	Fair	Some	Low	High	Easy	High
Beta-ray	Good	Ltd.	No	Yes	Good	Some	Low	High	Easy	High

Sensors can be categorized generally as being either physical or chemical in nature. Physical sensors are used to measure a range of physical responses such as temperature and pressure. In addition to the most common types of physical sensors, optical and electrical, the category includes geometric, mechanical, thermal, and hydraulic types. Sensors that detect electrical activity include electrodes. Optical sensors are being used in a number of applications in which light is used to collect physical data. They are a key element of certain new technologies.

To select the correct sensor you should know something about how the different sensors work (accuracy, repeatability, environmental effect, etc.), and which is used for what application. This is important since not all sensors measure the same way. The three most common sensors used down-stream is nuclear, infrared, and caliper. There are also specialized types such as microwave, laser, X-ray, and ultrasonic. They sense different conditions for operating equipment (temperature, time, pressure, dimensions, output rate, etc.) and also sense color, smoothness, haze, gloss, moisture, dimensions, and many more.

Sensitivity and complexity increased as advances were made in electronics technology, including innovative circuit designs and more efficient power sources that followed the invention of vacuum tubes and transistors. Sensors today are evolving more rapidly than ever with the result of microcircuits and nanotechnology, improved materials, and new design capabilities. Microfabrication and nanotechnology in recent years have had a significant impact on sensors. Microfabrication technology can be used to produce geometrically well-defined, highly reproducible structures and surface areas. Consequently, this may simplify or minimize the need for individual calibration.[151-154]

Chemical sensors are designed to detect or measure the presence of specific chemical compounds. This category includes gas and electrochemical devices. Photometric sensors, which are optical sensors used to measure chemical presence, are also included in this category.

Pressure Sensor

Important in the processing lines is controlling pressure. Pressure sensors are used from the feeding lines to plasticators to downstream equipment to improve melt quality, output rate, enhance product performance and quality, and minimize material waste.[156] There are basically two types of pressure sensors used: strain gauge and piezoelectric pressure sensing devices. Each has their advantages and disadvantages. The strain gauges are best with long fabricating times, used without special wiring, they are rugged, and lower in cost than piezoelectric sensors. The ability to splice wiring and low replacement costs makes them ideal for rapid die/mold changes and harsh environments.

A piezoelectric sensor performance is best for short cycle times, high temperatures, and critical part control. The sensors are smaller than strain gages so they can be used in tight spaces and are immune to high electrical discharge and radio frequency noise. They require balanced wiring, charge amplifiers and careful attention to ground loops. Piezoelectric sensors have quicker response times, typically greater than 20 kHz, versus 0.2 kHz for strain gauges.[472]

These sensors play a critical role at every stage of the fabricating process and because the process, such as the pressure of the process affects the physical properties of a plastic material, controlling pressure is critical. Pressure translates into heat and shear, which can significantly change physical properties and even chemical properties in the finished product. Pressure sensors can help solve these control problems. In many processes, the critical pressure points to measure depend on your technical knowledge and ability to justify the expense of time, personnel, and equipment. An important aspect is to optimize the number and location for pressure sensors. They provide the means to ensure that plastics and machine time are put to the optimum use, and that production of quality parts is maintained.

Because pressure transducers from different manufacturers can vary significantly, it is important to understand their performances such as accuracy. An ideal device would have a direct linear relationship between pressure and output voltage. In reality, there will always be some deviations; this is referred to as nonlinearly. The best straight line is fitted to the nonlinear curve. The deviation is quoted in their specifications and expressed as a percent of full scale. The nonlinear calibration curve is determined in ascending direction from zero to full rating. This pressure will be slightly different from the pressure measured in descending mode. This difference is termed hysteresis; it can be reduced via electrical circuits.

Temperature Sensor

Fabricating plastic products is a thermal process with the major task to ultimately control temperature. Too much or too little heat at the wrong place can cause many problems. Understanding these temperature characteristic behaviors is important to successful fabrication. Pinpointing temperature accuracy is essential. In order to achieve it, microprocessor based temperature controllers can use a proportional-integrated-derivative (PID) control algorithm acknowledged to be accurate. The unit will instantly identify varying thermal behavior and adjust its PID values accordingly.[3, 153]

It is generally recognized that increasing temperature of plastics increases their atomic vibration and molecular mobility resulting in reduced melt viscosity. Thus, as an example, during plastication when a plastic melt is too viscous, the first reaction could be to increase the temperature of the melt. The effect of molecular weight distribution (MWD) on this relationship becomes complex. With PEs broadening the MWD decreases the sensitivity of melt viscosity to temperatures, whereas with PSs broadening the MWD increases temperature sensitivity. Methods of expressing molecular averages and distributions, and the combined effects of branching, may be responsible for the discrepancy (Chapter 1).

You cannot see this thermal energy, only its effects. Thermal energy radiates in the IR spectrum, outside the spectrum of visible light. Use has been made of IR video cameras to detect energy color patterns in all locations around the machine and auxiliary equipment. With this IR thermography every plastic has its own wavelength and temperature readings are related to the IR color patterns. It also provides IR signatures for each plastic using the Fourier Transfer Infrared Spectrum (FTIR).

Temperatures can be measured with thermocouple (T/C) or resistance temperature detector (RTD). RTD provides for stability; its variation in temperature is both repeatable and predictable. T/Cs tend to have shorter response time, while RTDs have less drift and are easier to calibrate. RTD provides for stability; its variation in temperature is both repeatable and predictable. RTD contains a temperature sensor made from a material such as high purity platinum wire; resistance of the wire changes rapidly with temperatures. These sensors are about 60 times more sensitive than thermocouples.

The thermisters (TMs) are semiconductor device with a high resistance dependence on temperature. They may be calibrated as a thermometer. The semiconductor sensor exhibits a large change in resistance that is proportional to a small change in temperature. Normally TMs have negative thermal coefficients. Like RTDs, they operate on the principle that the electrical resistance of a conductive metal is driven by changes in temperatures. Variations in the conductor's electrical resistance are thus interpreted and quantified, as changes in temperature occur.

A T/C is a thermoelectric heat-sensing instrument used for measuring temperature in or on equipment such as the plasticator, mold, die, preheater, melt, etc. T/C depends on the fact that every type of metallic electrical conductor has a characteristic barrier potential. Whenever two different metals are joined together, there will be a net electrical potential at the junction. This potential changes with temperature.

Trying to measure the melt temperature could be deceiving. As an example an extrudate with a room temperature T/C pyrometer probe will often give a false reading because when the cold probe is inserted, it becomes sheathed with the plastic that has been cooled by the probe. A more effective method is by using what some call the 30/30 method. One simply raises the temperature of the probe about 30F (15C) above the melt temperature and then keep the probe surrounded with hot melt for 30 s. The easiest way to preheat the probe is to place the probe on, near, or in a hole in the die.

By preheating above the anticipated temperature, just prior to inserting it into the melt, then it requires the probe to actually be cooled by the melt. The lowest temperature reached will be the stock temperature. It also helps to move the probe around in the melt to have the probe more quickly reach a state of equilibrium. To be more accurate, repeat the procedure.

Traditionally, PID controls have been used for heating and on-off control for cooling. From a temperature control point the more recent use is the fuzzy logic control (FLC). One of FLCs major advantage is the lack of overshoot on startup, resulting in achieving the setpoint more rapidly. Another advantage is in its multi-variable control where more than one measured input variable can effect the desired output result. This is an important and unique feature. With PID one measured variable affects a single output variable. Two or more PIDs may be used in a cascade fashion but with more variables they are not practical to use.

Fuzzy Logic
Different logic control systems are used. An example is the fuzzy logic control (FLC) that provides a way of expressing non-probabilistic uncertainties. Fuzzy theory has developed and found application in database management, operations analysis, decision support systems, signal processing, data classifications, computer vision, etc. However, the application that has attracted most attention is control. FLC is being applied industrially in an increasing number of processing plants. The early work in FLC was motivated by a desire to directly express the control actions of an experienced operator in the controller and to obtain smooth interpolation between discrete controller outputs.

FLC system approach can be used to solve problems. Many applications of FLC are related to simple control algorithms such as the PID controller. In a natural way, nonlinearities and exceptions are included which are difficult to realize when using conventional controllers. In conventional control, many additional measures have to be included for the proper functioning of the controller: anti-resist windup, proportional action, retarded integral action, etc. These enhancements of the simple PID controller are based on long-lasting experience and the interface of continuous control and discrete control. The fuzzy PID-like controller provides a natural way to applied controls. The fuzzy controller is described as a nonlinear mapping.

Temperature Controller

For temperature controllers to obtain quality-fabricated products requires accuracy on their dynamic behavior such as response time and transient performances. Most controllers provide a derivative term that is called the rate term. This is an anticipatory characteristic that shortens the response time to changing conditions. There is also a circuit that limits overshooting. Controllers can differ widely depending on requirements such as short response time, minimal overshooting, high circuit stability even with system (equipment and plastic) variations, transient suppression, and sluggishness to keep temperature variations small.

The art of trade-off has to be accepted in the adjustment of controllers and in the selection of suitable control elements. This action is taken since not all demands can be met in an optimal manner at the same time. Controllers operate in a digital mode and employ microprocessors. The input signal is converted into a numerical value and mathematically manipulated. The results are summarized to obtain an output signal. This signal regulates the power output in such a way that the temperature is maintained at the set value.[155]

A calibration check of controllers should be made on a regular basis. The ISO 9000 standard reviews developing the frequency calibration checks. A visual examination should be made before proceeding with the check to determine that no damage exists. Some of the more common problems caused by a plant's hostile environment that can effect equipment such as sensors/transducers are noise interference, mounting holes (must be concentric and clean), installation, diaphragm considerations, and transducer calibration. Zero balance, full-scale sensitivity, and R-cal at 80% parameter reference points for calibration can be used. The sensor/transducer manufacturer provides these parameters.[154]

Processing Window

Regardless of the type of controls available, the processor setting up a machine uses a systematic approach based on experience or that should be outlined in the machine and/or control manual. It is a defined area or volume in a processing system's PC pattern. Within this window fabricated products meet performance/cost requirements. Note that a major cause for problems with any process can be that the process operates outside of their required operating window.

Once the machine is operating, the processor methodically makes one change at a time, to determine the result for each change. It provides a range of processing conditions such as melt temperature, pressure, shear rate, etc. within which a specific plastic can be fabricated with acceptable and optimum properties. As reviewed in Chapter 4 (Machine start-up/Shut-down – Maximizing Processing Window Control) windows such as a molding area diagram (MAD) and molding volume diagram (MVD) can be used during injection molding. This IM approach using a processing window can be applied to the other processes (extrusion, blow molding, etc.).

The term PC is often used when machine control is actually performed. As the knowledge base of the fundamentals of the fabricating process continues to grow, the control approach is moving away from press control and closer to real process control where material response is monitored and then moderated or even managed. The fabricator should note that changes in process parameters, such as injection rate, could have dramatic effects on moldings, especially mechanical properties, meeting tolerances, and surface properties.

When making processing changes, have patience by allowing enough time to achieve a steady state in the complete fabricating line before collecting data. It may be important to change one processing parameter at a time. As an example with one change such as extruder screw speed, temperature zone setting, cooling roll speed, blown film internal air pressure, or another parameter, allow four time constants to achieve a steady state prior to collecting data.

Lines can operate with different degrees of automation via computer-integrated PCs providing improvements in operating procedures and quality assurance with the result that rejects are reduced (if not eliminated) and fabricating costs are usually reduced. These closed loop systems maintain long term repeatability of factors such as melt velocity and pressure. All this action occurs independent of what could be occurring with equipment component wear, unbalance of equipment in the line, and/or plastic material variations.

Usually elaborate control systems cannot correct for problems such as those caused by a:

1 worn screw and barrel;
2 inadequate drive torque; and/or
3 poor screw design.

As an example, such systems will not yield good temperature control unless all features essential to good control are well maintained. Obviously, burnt out heating elements cannot be tolerated. Other factors of these type also exist.

Control and Monitoring

The different fabricating processes have their own process controls that have the common purpose to produce products that provide meeting performance requirements at the lowest cost. The following review concerns controlling injection molding (IM) that has many factors to consider and can be related to other processes.[304] It describes Moldflow Corp's Manufacturing Solutions for the automation, control, and monitoring of the IM process, the problems they solve, the methods used to solve those problems, and the way in which they add value to the IM process.[158] The Manufacturing Solutions suite consists of three distinct products:

1 The Moldflow Plastics Xpert® (MPX™) process automation and control system decreases mold setup time, cycle time, and scrap, and improves molded part quality and labor productivity. Unlike traditional trial-and-error methods, MPX tools provide a consistent and systematic method for improving and optimizing the molding process.

2 The Moldflow Shotscope® process monitoring and analysis system collects critical data in real time from injection molding machines on the factory floor, then records, analyzes, reports, and allows access to the information for use in critical decision making.

3 The Moldflow EZ-Track™ production monitoring and reporting system is a product for real-time, plantwide production monitoring and reporting. The EZ-Track system can be attached to virtually any cyclic manufacturing equipment and machinery.

In response to market feedback regarding existing plastic manufacturing practices, Moldflow developed a complete suite of manufacturing solutions for the automation, control, and monitoring of the injection molding process. Custom and captive injection molders wanted a suite of products from one global supplier that would provide IM manufacturing personnel with all the tools necessary for the scheduling, setup, optimization, control, and reporting of the IM process. Specifically, customers pointed out that existing molding practices often resulted in:

1 inefficient scheduling of mold, machines, and labor resources;

2 long process setup times and associated scrap;

3 non-optimized cycle times;

4 unacceptable molded part quality;

5 unacceptable production scrap rates;

6 poor or inconsistent control of the molding process;
7 lack of part traceability;
8 lack of manufacturing management information.

These Manufacturing Solutions products examines problems with scalable solutions that will work for small, custom injection molders and large, multi-national corporations alike. The following sections provide an overview of the IM industry and descriptions of how the Manufacturing Solutions products address these problems. The plastic IM process is integral to many of today's mainstream manufacturing processes. While demand for IM plastic parts is increasing, the problems associated with the process can often cause significant time delays and cost increases. This is because the IM process is a complex mix of machine variables, mold complexity, operator skills, and plastic material properties, and there are constant pressures to reduce mold setup times and scrap, improve part quality, and maximize the productivity of every IMM (IM machine). Because of this, it is becoming increasingly important to have systems in place to allow the molding process to be scheduled, set up, optimized, controlled, and monitored with an intuitive, systematic, documentable, and globally supported method.

Such a system must be intuitive, so machine operators can maximize productivity by not having to be experts on every machine/mold combination they are responsible for running. It must be systematic, so the process of setting up and optimizing the molding process can be done with a scientific method that does not rely solely on the skills of the machine operator. It must be documentable in order to meet the strict quality control reporting requirements that are commonplace today. Finally, the system must be globally supported so those large, multi-national corporations can source these solutions from one-supplier and implement company-wide standards across their enterprises.

The following sections present a brief overview of each of the Manufacturing Solutions products, the problems they solve, the methods used to solve those problems, and the way in which they add value to the IM process.

In an all-too-common occurrence throughout the IM industry today, the number of molds that must be set up and optimized for high-volume part production is far outpacing the number of process engineers or trained technicians qualified to do so. It is not uncommon for a molding operation to have a small number of individuals with the education or experience to set up the injection molding process. Even those who can set up the process often do not have time to optimize it due to production pressures. This results in problems such as long process setup times and associated scrap, non-optimized cycle times, unacceptable molded part quality, unacceptable production scrap rates, and poor or inconsistent control of the molding process.

Moldflow Plastics Xpert (MPX) process automation and control technology provides machine operators with an easy-to-learn and easy-to-use tool for the setup, optimization, and control of the IM process. Finally, a tool exists that allows a less-experienced operator to set up molds, optimize the process, and control production.

MPX functionality is arranged into three modules, the first of which is the Setup Xpert, a module that allows users to perform a variety of injection-velocity- and pressure-phase-related setup routines to fix certain defects, such as short shots, flash, burn marks, sink marks, etc. The objective of Setup Xpert is to achieve one good molded part with no defects. The basic process is that a user molds a part, then provides feedback to the MPX system regarding molded part quality. The MPX system then processes this feedback along with data being collected from the machine and (if necessary) determines a process change that will improve the result.

After completing Setup Xpert and determining a combination of processing parameters which results in a single good molded part, the user still does not know if these parameters are within a robust processing window. For example, any process parameter drift or variation could easily result in parts of unacceptable quality. In the IM process, variation is inherent. Whether the material, the machine, the process, the operator, or the environment causes it, there will always be some variation. This variation may or may not result in the production of bad parts. The variation is normal, so the processing window must be robust enough to compensate for it without producing bad parts.

It is common knowledge that design of experiments (DOE) is a useful tool in the fight to find a robust processing window. The process window basically is defined as the maximum amount of allowable process variation that still will not result in the production of bad parts. However, the historical perception of DOE is that it can be complicated, resulting in extensive training requirements and costs for those responsible for running it, and time consuming, thus increasing the time required to put a given mold into production.

The second module in the MPX system is the Optimize Xpert. Simply put, the Optimize Xpert is an automated design of experiments (DOE) that can be run quickly and easily, and it does not require any special training in statistical process control. The goal of Optimize Xpert is to obtain a robust processing window, which will compensate for normal process variation and ensure that acceptable quality parts are produced consistently.

While the Optimize Xpert DOE is automated, easy to use, and relatively fast to complete, it is far from simple. There are five process parameters that can be used as DOE factors: packing pressure, mean (or average) injection velocity, velocity stroke, packing time, and cooling time. In addition, there are a number of molding defects that can be used to measure part quality criteria, including short shots, flash, sink marks, burn marks, poor weld line appearance, weight, dimension, and warpage problems. Assuming a robust processing window is determined using the Optimize Xpert, control mechanisms are still required to make sure that the process stays within its specified limits.

The third module in the MPX system is the Production Xpert. The Production Xpert is a comprehensive process-control system that maintains the optimized processing conditions determined with Optimize Xpert. Production Xpert allows the user to maintain the production process consistently, resulting in reduced reject rates, higher part quality, and more efficient use of machine time. If desired, the Production Xpert will correct the process automatically should it drift or go out of control. One goes through MPX to set up, optimize, and control the IM process.

There are still many functions required in a manufacturing operation, including production scheduling, process monitoring, statistical process control (SPC), statistical quality control (SQC), scrap tracking, production monitoring and reporting, preventive maintenance scheduling, etc. Moldflow meets these requirements with two additional Manufacturing Solutions products, which are described in the following sections.

The Shotscope process monitoring and analysis system collects critical data in real time from IMMs (injection molding machines) on the factory floor, then records, analyzes, reports, and allows access to the information for use in critical decision making.

The Shotscope system allows injection molders to maximize their productivity by providing the tools necessary to schedule mold and machine resources efficiently and also to monitor the status and efficiency of any mold/machine combination. By monitoring the efficiency of a given mold/machine combination, molders can schedule jobs based on a number of criteria, including minimum cycle times, highest production yields, etc. Users also can define periodic maintenance schedules for molds and machines, and, after a pre-determined number of cycles or operating hours, Shotscope will signal that preventive maintenance is required.

The Shotscope system also maintains and displays statistical process control (SPC) data in a variety of formats, including trend charts, X-bar and R charts, histograms, and scatter diagrams. This information provides molders with the knowledge that their processes are in control, and, should they go out of control, Shotscope can alert to an out-of-control condition and divert suspect-quality parts. Furthermore, because the Shotscope system can measure and archive up to 50 process parameters (such as pressures, temperatures, times, etc.) for every shot monitored and the information archived, the processing "fingerprint" for any part can be stored and retrieved at any time in the future. This functionality is extremely important to any manufacturer concerned with the potential failure of a molded part in its end-use application (for example, medical devices).

Finally, the Shotscope system contains a reporting mechanism that allows all the data collected and entered into the system to be communicated across a manufacturing enterprise, so that informed decisions can be made. Users can generate production, scrap, downtime, efficiency, and job summary reports, any of which also can be used as documentation that accompanies part shipments.

The third product in the Manufacturing Solutions suite is the Moldflow EZ-Track system, a product for real-time, plant-wide production monitoring and reporting. It is truly plant-wide, because the EZ-Track system can be attached to virtually any cyclic manufacturing equipment and machinery, such as ultrasonic welders, assembly machines, packaging equipment, etc., in addition to injection molding machines. The EZ-Track system provides a scalable solution for production monitoring, which can be used by small, custom molders with fewer than 10 machines or by large, multi-national corporations with distributed IM and manufacturing operations around the world. There are extensive setup capabilities that allow complete definition of resources and flexible customization of most displays and reports.

The EZ-Track system collects data on cycle times, cycle/part counts, and number of rejects, and it uses this data as the foundation to perform powerful scheduling tasks. The EZ-Track scheduler can check for mold conflicts and machine feasibility and highlight any problems, as well as continuously update estimates of job completion times based on actual cycle time, downtime, rejects, and cavitation. In addition, the scheduler also supports family molds.

The EZ-Track system monitors machine status, downtime, scrap, raw material usage, and labor activity. It can also be used to track machine efficiencies and compute yield efficiencies. Labor, time, and attendance can be tracked by employees and associated with machines, jobs, and activities. In this way, manufacturing managers can determine what jobs, machines, or activities require more labor resources than others. This then allows them to investigate areas where more efficiency, possibly in the form of process automation, could be introduced into their manufacturing operations.

The EZ-Track system can also be used to count good parts, diverted parts, packed cases, etc. Downtime is measured automatically and can be classified into an unlimited number of causes. Once production data is collected, there is an extensive set of Web-based reports that can incorporate trend charts, tabular reports, pie charts, and Pareto charts. Finally, it is possible to interface the EZ-Track system to ERP/MRP systems via an advanced SQL database that is open, fully documented, and ODBC-compliant. Not only is the EZ-Track system scalable from small to large numbers of molding machines and other types of cyclical manufacturing equipment, it also can play an important role in sending real-time production data to company-wide ERP/MRP systems.

There are many companies today across a broad range of industries for which plastic injection molding and related upstream and downstream manufacturing processes are on the critical path to achieving successful and profitable product launches. These companies face a variety of issues that make it difficult to remain competitive:

1 product life cycles are decreasing while short-term volume requirements are increasing exponentially,
2 customers continue to demand increased quality at lower costs,
3 there is a shortage of skilled labor to run ever-more-sophisticated IM equipment,
4 inefficiencies in the scheduling, monitoring, and reporting of production do not allow for efficient manufacturing management,
5 molded part process documentation and traceability increasingly is becoming a standard requirement.

These companies require tools that are intuitive, systematic, documentable, and globally supported to remain competitive on a global scale. Moldflow's Manufacturing Solutions products directly address these needs. The Plastics Xpert system applies and automates the process of scientific molding to decrease mold setup time, cycle time, and scrap, and to improve molded part quality and labor productivity. The Shotscope process monitoring and analysis system collects critical data in real time from injection molding machines on the factory floor, then records, analyzes, reports, and allows access to the information for use in critical decision making. The EZ-Track production monitoring and reporting system enables real-time, plant-wide production monitoring and reporting.

For the latest information on all of the Moldflow Manufacturing Solutions and Design Solutions products, visit http://www.moldflow.com.

Process Controller

In summarizing the technology of PCs it can be said that the solid state controller consists of a set of base functions. They all require a programming method, logic engine, operator interface, communication interfaces to I/O with a programming system, an operating system, and a hardware platform/package. To make an informed decision on which controller is best for an application, it is important to understand that for each controller there is a choice regarding their different levels of risk or responsibility. With low user risk, there is higher vendor responsibility; with higher risk there is lower vendor responsibility.[159]

This range of vendor-to-user responsibility is an essential consideration for making an informed hardware choice. There are choices available for both controllers and the functions within them. The fundamental set of requirements involve speed, scale, packaging, reliability, and peripherals. These requirements must be satisfied before successfully applying any control system technology.

Control Choice

Control choices continue to provide many novel approaches. The users have to recognize what to specify such as soft, programmable, hybrid, wireless sensing/monitoring,[160, 161] or entirely new architectures. One should define control not by the PC box performing it, but rather by virtue of the problem it solves. To do this, users must consider the choices available at each level within a controller. The choice requires personal knowledge or help from a reliable source to determine which type of controller is appropriate for a specific application.

Today's programmable microprocessor controller operating systems are the result of about a half-century of evolution and provide the available repeatability and reliability required on the plant floor. In the past, achieving these objectives meant choosing a vendor-specific operating system and choosing that vendor's entire control system. This can be a benefit if risk is to be avoided, but can be detrimental if a high degree of in-house customization and integration is desired.

Intel Corp. basically started logical circuits of a microprocessor using a single silicon chip in 1969 in controlling injection molding machines (IMMs). Up to that time, in conventional logic control all sequential functions were programmed by means of an electrical wiring matrix. In a microprocessor control system this matrix is replaced by software that contains the instructions.

The processor is told how to process the signals from the operator panel. This signally action is linked with other process parameters that are stored in electronic memory modules. This sequence logic can be divided into individual independent blocks with separate microprocessors running their programs. By this multiprocessor technique that is a modular design, the microprocessor takes over the entire logic of the IMM whereby it has complete control in operating the machine producing products that meet performance to cost requirements.[162]

PCs are fairly simple devices to operate. If they do not function properly all kinds of problems develop. A checklist for eliminating problems includes: nonuniform processed plastic, heater element burnout, location and depth of sensor as related to response time, type of on/off control action such as proportional controller, set point control, and basic electrical component proper selection. It is important to have the proper depth of the sensor in a barrel in order to obtain the best reading for the melt; the deeper the better.

Where water is involved in a PC, as in mold/die cooling controllers, with improper construction the most common problem (due to expansion/contraction not properly incorporated) is that water leaks occur. With their external pressure relief valves, they ensure discharge outside the cabinet. With inside discharge, severe damage can occur to mechanical and electrical components.

Different computer designs are used. As an example there are computer coordinator controllers. These groups of controllers are connected together so that they may all be changed at the same time from a single point. Also used are multi-zone microprocessors that monitor temperature, pressure, output rate, etc. that send either independently or coordinated signals from several sensors to achieve a more reliable and efficient performance. The microprocessor has to carry out control and monitoring functions such as:

1 standard sequence control, timer, temperature, malfunction indication, etc. functions;

2 monitoring functions such as self-diagnosis of malfunctions, control of setup procedures, calculation of operating data, troubleshooting, etc.,

3 control functions such as different temperatures or pressures in a mold/die, output speed, melt consistency, etc.).

What is required of this equipment is to ensure that all its actions include what has to be carried out to produce the required products. Determining operating points by trial and error is inevitably eliminated.

Intelligent Processing

The target during fabricating (design, etc.) is to cut inefficiency, such as the variables, and in turn cut the costs associated with them. The intelligent processing (IP) approach is a technology that utilizes sensors, expert systems, and process models which control processing conditions as materials are produced and processed without the need for human control or monitoring. Sensors and expert systems are not new in themselves. What is new is the manner in which they are put together (temperature, pressure, and other variables). In IP, new nondestructive evaluation sensors are used to monitor the development of a material's microstructure as it evolves during production in real time. These sensors can indicate whether the microstructure is developing properly. Poor microstructure will lead to defects in materials. In essence, the sensors are inspecting the material on-line before the product is produced.

Information from these sensors and data from conventional sensors that monitor are gathered and sent to a computerized decision making system. This decision-maker includes an expert system and a mathematical model of the process. The system then makes any changes necessary in the production process to ensure the material's structure is forming properly. These might include changing temperature or pressure profiles, or altering other variables that will lead to a defect-free fabricated product.

With IP different benefits occur such as a marked improvement in overall product quality and a reduction in the number of rejected parts, thus reducing cost. It is important to note that IP involves building in quality rather than attempting to obtain it by inspecting a product after it is manufactured. The result is reducing post-manufacturing inspection costs and time. Being able to change manufacturing processes or the types of material being produced is another potential benefit of IP.

Intelligent Setting and Control

IP is applicable to different processes. The following review concerns injection molding (IM) that can be related to other processes. IM when compared to other processes requires rather sophisticated controls to produce products meeting performance requirements at the lowest cost. The need to change the way injection molding machines (IMMs) are initially set for a new job was recognized by the industry in the mid 1980's. As reviewed by Anne Bernhardt of Plastics & Computer Inc. (P&C),[145] originally CAE analysis with machine settings was used. To further advance PC an expert system was developed to assist the settings of IMMs by an operator interface that requires a description of the mold and the part features.

This action occurred because the IM industry has always been pushed by demands for higher levels of product quality and productivity, both obtained and maintained without the costly errors and corrections experimented with by many users and processors. Unfortunately, its implementation is very challenging due to the complexity of the IM process. The governing input variables (material and equipment) are not generally measured directly, and the output (properties in terms of dimensions, appearance, strength, etc.) is difficult to measure directly, especially in a real time.

The solution to the problem required:

1 determine for each specific application, all parameters of the process that influence part quality;

2 assess relationship of these parameters to the ones used by the IMM controls;

3 inform the machine controls on all possible quality problems in the shortest possible time;

4 program the IMM controls to react to each changing situation.

The evolution in this development has taken place by understanding two conditions. On the machine capability there are the requirements of more repeatability, more precise (multi-point) settings, self-tuning (closed loop) controls, statistical process controls (SPC), and the possibility to fully automate a molding cell with all the necessary auxiliaries. The other condition concerns the determination of the molding conditions that involve more precise modeling of the relationship between part/mold design, processing parameters, and quality/productivity values. It became clear that the self-regulation of machines could be effective only when the part/mold design were optimized, and when, at least, the major parameters required for the correct processing conditions have been pre-determined. It opened the way to computerized process simulation to replace the traditional trial and error method for molding optimization.

Program Analysis

This approach resulted in the development by C&P of a complete *TMconcept* analysis of filling, packing, and cooling in a microprocessor controlled IMM. It is important to understand that such activity is not confined to a simple re-organization of data, but requires an additional set of calculations.

For example, whereas the CAE calculations for the filling phase are based on the melt temperature entering the nozzle, in the best case where the FEA (finite element analysis) algorithm allows it, the machine settings to reach this temperature are affected by barrel temperature profile, screw speed, and back pressure. It calls for the use of empirical models to set parameters not considered by the typical CAE programs. A statistical method based on experimental data, previously developed for the TMconcept-MCO package for molding optimization, was taken for these calculations.[145] The machine characteristic database, already part of the package to estimate the moldability, was enlarged to define more precisely the process capability essential to the settings: such as, plasticating rate at different rpm.

What was required were:

1 the need for an interface between the FEA workstation and the molding machine; point

2 the need to replace the IMM with new generation machines equipped with advanced microprocessor controls; point

3 the lack of the complete set of CAE analyses for many commercial parts; or point

4 the recurrent problem of part design modifications during mold construction not included in the CAE analysis.

Points (1 and 2) became more moot since the advent of PCs has made the power of a workstation affordable to any molder. Many IM shops use PCs for production management systems, thereby simplifying the connection problem to the microprocessor of new machines that are gradually replacing the old ones. More analyses are made today so point (3) is less critical with point (4) developing.

Stand-alone systems were studied for the computation of the initial IMM settings with the inherent advantage in limiting errors when using a computerized system. Errors in machine settings are difficult to identify, and may cause not only production inefficiencies, but may even damage the mold and the machine. Two types of errors can be recognized. They are mistakes in data entry and mistakes due to insufficient knowledge.

The basic concept behind the development of the program was the realization that the initial setting of IMM parameters should be based on a description of the mold and part specifications instead of the process. This has the potential to eliminate two steps from the current traditional three-step process that requires the operator namely to understand the features of the mold, material, and part requirements; to look into one's experience for the parameters to be set for the above; and to enter the settings in the IMM controller.[1, 3, 143, 164]

The resulting program created a link between IMM capabilities, machine settings, and mold/part characteristics. The need to detect if a particular machine was certainly suitable for a specific job or not, was clear from the beginning. This situation is not typical, since the causes of machine inadequacy are not always directly evident. While the size of the tool is an obvious factor in the machine suitability, the clamping force requirements can remain questionable even with a complete set of the most advanced FEA analysis.[1] The latter must be integrated with part quality, cost considerations, and skilled judgment of the complete project.

Warning messages were an important part of the program from the beginning of its development. These messages indicate, with various degrees of probability, the potential for the occurrence of a particular problem, which helps the operator make a decision on how to handle a specific situation. Machine settings were integrated with problem analysis and strategy for continuous improvements. Along with the program development a quick-setup was added to the machine microprocessor so that the operator did not have to adjust all the parameters not strictly relevant to the molding process, but key to machine operation. In this way, reasonable values to avoid the risks due to unnecessary machine over-charging, are always set. Whenever necessary the operator can fine-tune these parameters.

This procedure highlights that no system can claim any initial settings as best IMM settings, regardless of the quality of previous calculations and operator experience: the complexity of the molding process makes this claim inappropriate to any experienced engineer. Fine-tuning is always possible. For critical production, one needs to consider the possibilities for continuous productivity improvement and molding process robustness.

Fuzzy Logic

To accomplish the above two major developments were made in the CAE programs. One development was the application of fuzzy logic in expert software to examine mold-filling simulations for potential processing problems and advise on ways to rectify them. The fuzzy logic was required because the correct judgment of a specific part quality parameter (shear stress) cannot be made without weighting other parameters such as local melt temperature and its variability.

Troubleshooting

The other development related to troubleshooting of defects to provide guidance to test and debug start-up and also solve problems in operations that had been running well. These defects are considered qualitative in nature, because the machine cannot detect them, but needs operator judgement. The system forces the operator to define the problem in terms of: occurrence (such as in one cavity), non-occurrence (not in other symmetrical location), where did it occur (near the gate, etc.), and when it occurs (from time to time).

Experience has shown that, once the problem is well described, the ability to find the right solution instead of providing a set of possible remedies is strictly connected to the knowledge of existing molding conditions. Therefore, the target is to have a way to keep track of the evolution of these conditions. The program starts the settings like its predecessor, provides a direct comparison of evolving parameters any time required by the operator, and asks to enter the quality conditions.

At current development levels, the operator must implement the solution where it could be made directly by the machine controls. For example, where too low shrinkage can be corrected by a decrease in holding pressure. Because one is concerned with the risks of automatic implementation, and believes that, at least for a long time to come, there will always be problems requiring manual operations. An example is material clogging the throat of the hopper; a problem which can be minimized by proper equipment design but never eliminated. Another is metal wear.[163]

Regardless, one thinks that an intelligent machine control should always explain the reasoning behind its suggestion. This is the essence of all intelligent actions, which by definition require judgement to solve situations that do not have a simple exact answer. The strategy for initial settings and fine-tuning includes consideration of energy requirements and optimizes this important aspect.

Prototyping model

When a plastic product is to be fabricated usually the first step is to create a model. This approach is similar to designs in other materials. A design is prepared and revised until it is an acceptable product functionwise and costwise. Many times, the products being designed incorporate features that exist in other products such as bosses, ribs, snap fits, etc., which include standard design practices such as using standard mold/die components and allow for shrinkages. Following the product model is creating the mold/die geometry (Chapter 17).[337–340, 343, 344]

The basic point of the preceding illustration is that there is a great amount of repetitive information flow in the design process. As a result, what is perceived to be an extremely creative process is actually very repetitive in nature. The types of analytical problems that are encountered in the mold/die design process generally fall into the sciences of fluid mechanics and heat-transfer theory.

These fields encompass many complicated mathematical functions and relationships that were too time-consuming to evaluate in manual or conventional designs. The ability of the computer to remember and execute these computations quickly has added a new dimension to the mold/die design process, allowing prospective design alternatives to be evaluated and simulated by computer rather than in the molding press. Computer aids [CAD/CAM/CAE/CIM[1]] are enabling the creative energies of plastic product and mold/die designers to be spent in producing better designs in shorter time periods rather than performing repetitive design tasks. CAD/CAM/CAE/CIM have bridged the gap between designer and tool (mold/die) maker benefiting the plastics industry as a whole.[410]

Safety

Throughout the plastic industry different aspects of safety exist that include machine safety, material safety, and fabricating plant safety. All these safety aspects highlight that safety in designing products, handling plastic materials, processing equipment, and fabricated products exist from the past into the future. Examples of the types and amount of accidents (machinery, manual handling of objects, falls, etc.) are updated yearly by the National Safety Council, Chicago, IL. Different software and websites are available that concern safety and plastics. [166–172, 371, 429, 456, 460]

4 INJECTION MOLDING

Introduction

The process of injection molding (IM) is used principally for processing unreinforced or glass fiber reinforced thermoplastics (TPs) and thermosets (TSs) (Figure 4.1). Up to at least 90wt% of all plastics processed are TPs. There are many different types or designs of IM machines (IMMs) that permit molding many different products based on factors such as quantities, sizes (such as auto bumpers to medical micro products), shapes (simple to complex), product performances, and/or economics.[1, 150, 157, 173–176, 476]

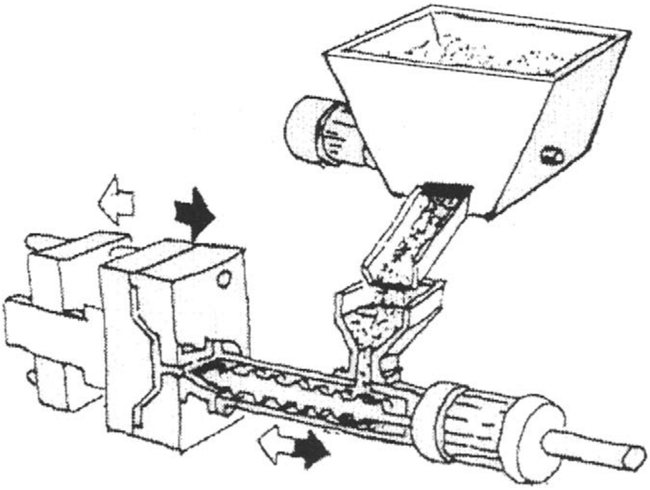


Figure 4.1 Schematic of an IM machine

Temperature melting/solidifying profiles are different for TPs and TSs. TP just melts in the plasticator and solidifies in the cooled mold. The

TS melts in the plasticator and cure to a harden state in the mold that operates at a higher temperature than the plasticator (Chapter 1). For the best controlled machines used for molding TSs the heated plasticator usually includes a water jacket to ensure that the melt temperature profile is under control.[3]

The term IM is an oversimplified description of a quite complicated process that is controllable within specified limits. Melted or plasticized plastic material is injected by force into a mold cavity (Figure 4.1). The mold may consist of a single cavity or a number of similar or dissimilar cavities, each connected to flow channels or runners which direct the flow of the melted plastic to the individual cavities (Chapter 17). The process is one of the most economical methods for mass production of simple to complex products. Three basic operations exist. They are the only operations in which the mechanical and thermal inputs of the injection equipment must be coordinated with the fundamental behavior properties of the plastic being processed. These three operations also are the prime determinants of the productivity of the process since manufacturing speed will depend on how fast we can heat the plastic to molding temperature, how fast we can inject it, and how long it takes to cool (or solidify) the product in the mold.

Melting (plasticating) the plastic is accomplished in a plasticator (screw in barrel as described in Chapter 3). This melt is forced into a clamped mold cavity. The liquid, molten plastic from the injection cylinder of the injection machine is transferred through various flow channels into the cavities of a mold where it is finally shaped into the desired object by the confines of the mold cavity. What makes this apparently simple operation complex is the limitations of the hydraulic or electrical circuitry used in the actuation of the injection plunger and the complicated flow paths involved in the filling of the mold (Chapter 17). Finally opening the mold to eject the plastic after keeping the material confined under pressure as the heat in the melt is removed to solidify the plastic into the shape desired.

The other operations such as feeding the machine, clamping the mold, etc., are also important. The basic machine is made up of the clamping end (fixed and movable platens); on the other end the injection unit of an inline IMM. The mold area is located in the center section (Figure 4.2). The empty space (cavity) in the mold is filled with melted plastic under high pressure. The clamping force on the mold halves is generated by the hydraulic and/or electric mechanism pushing against the moving platen.

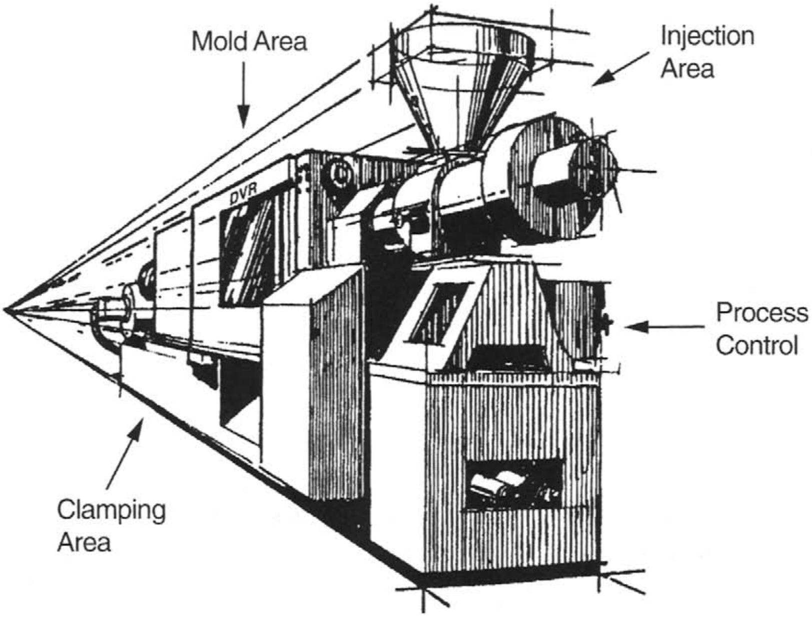


Figure 4.2 Three basic parts of an injection molding machine (courtesy of Plastics FALLO)

The part taken from the mold is, in most cases, a finished product ready to be packed and shipped or ready to be used as a part of an assembled unit. In contrast to metal forming, there is very little if any wasted material in injection molding. For cold runner TP systems most runners and sprues are reground and reused. By using hot runner molds, the sprue and runner systems remain in a melted state in the mold and become part of the next finished part (Chapter 17). The hot runners can be thought of as an extension of the plasticizing chamber.

IM lends itself readily to automation in varying degrees, depending upon the ingenuity of the machine and mold designers. The machine manufacturer can usually add components to the basic machine to implement any desired automatic arrangement. Molding cycles are relatively fast, and with new mold design developments constantly in progress, and centering on faster heat transfer within the mold, the molding cycle is continually being reduced.

Modern methods of material handling, both of the raw plastic and the finished product, are becoming more generally employed, further reducing costs of the finished part (Chapter 18). The reduction of raw material inventory is seriously considered, and studies of production control methods are no longer uncommon, even by the small molder. Methods such as these are important in making molded parts less expensive to manufacture.

Plastic is usually purchased in pellet form and heated in the plasticizer and/or preheated prior to entering the plasticator until it reaches a viscous state in which it can be forced to flow into the mold cavities. Each plastic differs in its ability to flow under heat and pressure. For the best result, correct melting temperature, injection pressure, and mold filling speed must be determined from experience or by trial for the particular plastic and mold used. Some molding conditions require that both the speed of injection and injection pressure varies during the filling process. A heat-sensitive plastic may be degraded if too fast a fill rate is used. Forcing the plastic through orifices at too high a velocity may increase the shear and temperature enough to cause overheating and burning.

Thin-walled parts require a fast fill rate to prevent chilling of the plastic before the cavity has properly filled. Some molded parts carry both thin and thick sections, plus such interrupted flow patterns as are required to move around cored holes. Demanding requirements such as these require considerable versatility in the design of the IMM injection unit. The programming of different injection speeds and pressures during the forward travel of the screw or plunger greatly aids in filling cavities properly. Programming or multi-stage injection is standard equipment on most machines.

The clamp tonnage of a machine must have sufficient locking force not to cause the parting of mold halves; it resists the force of melted plastic moving at high pressures into the mold halves. If the mating surfaces of the mold are forced apart, even a few thousands of an inch (depending on type plastic), fluid plastic will flow out and produce flash (Chapter 17).

Molding system

The IMM process can be identified by its most basic three popular methods of operation that are the hydraulic, electrical, and hybrid types. The two basic plasticizing systems used are the single-stage and the two-stage molding systems (Figures 4.3 and 4.4); there are also 3-stage molding units, etc. The single-stage is also known as the reciprocating screw IMM. The two-stage has other names such as the piggyback IMM that can partially be related more to a continuous extruder (Chapters 3 and 5).

Different IMMs meet different qualitative requirements to mold specific parts such as dry cycle, injection rate, injection pressure,

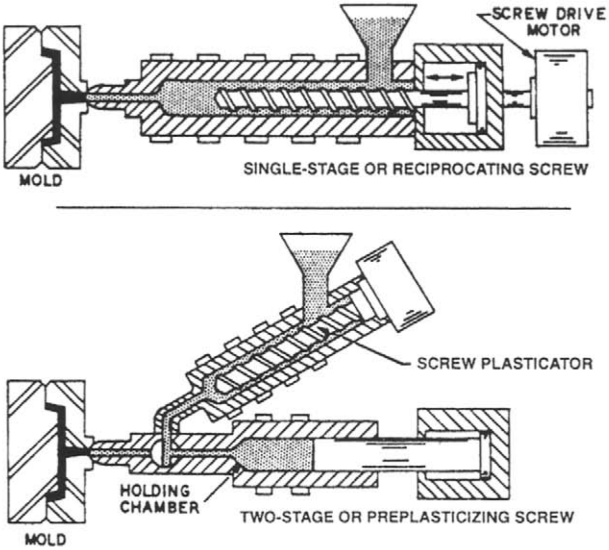

SCREW DRIVE MOTOR
MOLD
SINGLE-STAGE OR RECIPROCATING SCREW
SCREW PLASTICATOR
HOLDING CHAMBER
TWO-STAGE OR PREPLASTICIZING SCREW
MOLD

Figure 4.3 Schematics of single and two-stage plasticators

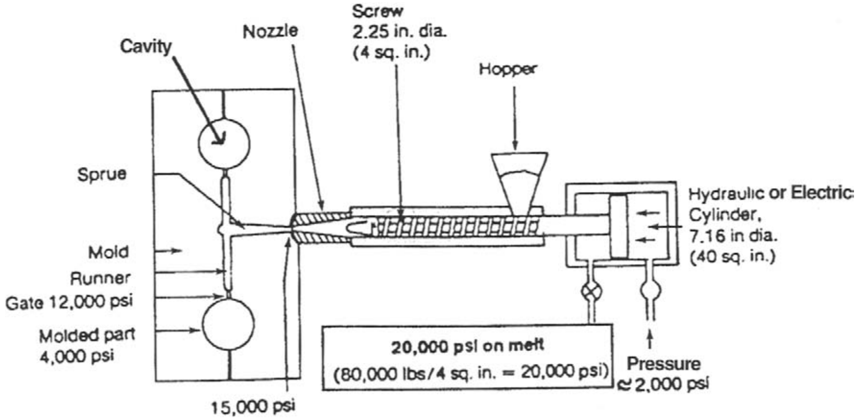

Screw
2.25 in. dia.
(4 sq. in.)
Cavity
Nozzle
Hopper
Sprue
Mold
Runner
Gate 12,000 psi
Molded part
4,000 psi
Hydraulic or Electric
Cylinder,
7.16 in dia.
(40 sq. in.)
20,000 psi on melt
(80,000 lbs/4 sq. in. = 20,000 psi)
Pressure
≈2,000 psi
15,000 psi

Figure 4.4 Simplified plastic flow through a single-stage IMM

clamping force, platen size and daylight opening, maximum screw stroke, etc.[3] The feature of shot size or IMM capacity represents the maximum usable volume of melt that is injected into the mold. It is usually about 30 to 70% of the actual available volume in the plasticator. The difference basically relates to the plastic materials melt behavior, and provides a backup safety factor to meet different mold packing conditions. Shot size capacity may be given in terms of the maximum weight that can be injected into a mold cavity(s), usually quoted in ounces or grams of general purpose polystyrene (GPPS). Since plastics have different densities, the better way to express shot size is in terms of the volume (in.^{3} or cm^3) of melt that can be injected into a mold at a specific pressure. Rate of injecting the shot relates to IMM's speed and also the process control capability of cycling the melt to move fast-slow-fast, slow-fast, etc. into the mold cavity(s).

Injection pressure in the barrel can range at least from 2,000 to some plastics up to 45,000 psi (14 to 310 MPa). The characteristic of the plastic being processed defines what pressure is required in the mold to obtain acceptable products. Based on what cavity pressure is required, the barrel pressure has to be high enough to meet pressure flow restrictions going from the plasticator into the mold cavity(s).

The molding cycle is the complete repeating sequence of operations in the process. One cycle represents the time period, or elapsed time, between a certain point in one cycle and the same point in the next. Most of the time is the cooling phase that is usually at least 60%. To shorten cycle time lies principally in assessing all the capabilities of the IM process in addition to designing the part and the mold. Thus what is needed is a device for achieving optimum designs of part and mold. Program systems that provide for computer simulation of the IM process are used for this purpose.[3] The availability and performance of relevant software programs provide guidelines so that one can develop continuing experience. In support of this approach are software programs to reduce cycle time by evaluating the actual IM process operational settings.

Oil hydraulic systems have been the major method used in operating IMMs. All electrical machines as well as hybrid (hydraulic/electrical) are now also used. Electric and hybrid eliminate many variables from the hydraulically operating IMMs.[3, 175]

Clamping Design

Controllable actions of IMM clamps exist. Their operating mechanisms are identified as mechanical or toggle, hydraulic, electrical, and hybrid (hydromechanical) (Figure 4.5). Each has advantages and disadvantages.[3] Toggle clamps are more popular in smaller-tonnage machines because the mechanisms are inexpensive to manufacture and require less-complicated circuitry. Most electric IMMs use toggles.

Hydraulic clamps are used extensively on machines in the medium-capacity range of about 150 through 1000 tons, with highest predominance in the 250 to 700 ton range. They offer flexibility in machine setup and operation. Since tonnage can be developed at any point along the clamp stroke, just setting limit switches at the desired points along a calibrated scale does mold setup. Clamp slowdown, mold

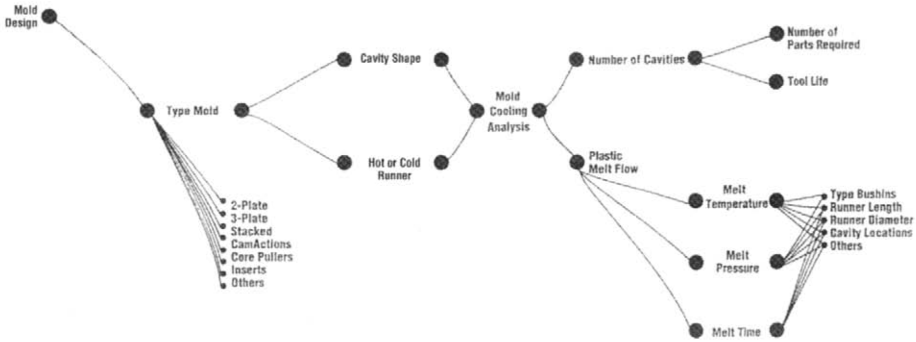

Mold Design
Type Mold
2-Plate
3-Plate
Stacked
CamActions
Core Pullers
Inserts
Others
Cavity Shape
Hot or Cold Runner
Mold Cooling Analysis
Number of Cavities
Number of Parts Required
Tool Life
Plastic Melt Flow
Melt Temperature
Melt Pressure
Melt Time
Type Bushins
Runner Length
Runner Diameter
Cavity Locations
Others

Figure 4.5 Example of mold operation controls

close, slow-mold breakaway, and fast-open functions are all adjustable. This versatility is particularly useful in complicated molding applications: molds with core pulls or unscrewing dies, multiple plate molds, or delicate parts requiring careful mold handling.[3]

Electrical clean operating IMMs are available from many sources worldwide. In the past few decades the all-electrical IMMs have been producing all types, shapes, and size molded products. Different electrical designs are used. As an example servomotors are connected to the ballscrews through a heavy-duty timing belt and pulleys. Die height is set by a servo-driven, chain-and-sprocket arrangement. The plasticator is directly driven through a timing belt. Its design objective is high speed that meets the objective with sub-one-second dry-cycle times.[3]

The hybrid is a combination of hydraulic and electrical. In turn these basic systems provide many different IMM designs to meet different product requirements. Each system provides advantages such as fast moving of platens, reducing size of hydraulic cylinders, and/or reduced operating costs. Examples of these hybrid operating systems meet the molders different molding requirements. A popular example that has been used for many decades is the electric screw drive system design in hydraulic operating IMMs.[3]

Tiebar

The clamping tiebars (rods) can be used to support the fixed and movable platens on which the mold is attached. They serve as equally loaded tension support members of the clamp when the mold is closed. The open distance between tie rods through which the mold must fit and eject molded parts sets up the maximum outside dimensions of the mold that can be used. Different designs are used to meet different processing requirements such as permiting installing molds that would occupy the complete platen minus the tie rod circular areas. There are designs used to unlock one to all tiebars, those with one to four retractable tiebars, three tiebars, and the tiebarless where no tiebars are used. Tiebarless design is of a C-frame (also called U frame, open frame, etc.) construction targeted to provide clamping pressure and proper parallelism as well as operating platens. The fundamental purpose of these different actions is to provide faster automated mold changes (in and out of the IMMs). Each system provides its own advantages (and limitations) for specific operations required in the different operating IM plants.

During clamping and when applying pressure on the molds, the tie rods stretch. If everything is in balance, the platens and mold stretch evenly. The distance the rods stretch is directly proportional to the applied load. Sensors, such as electrical strain gauges, can be used to detect the stretch or load applied and if an unbalance situation occurs, an indicator can alert the operator or the process control system. Bar sensing can also be used as a means of signaling the switch from pack to hold pressures, a potential alternate or support to pressure transducer use.

In use are retractable tiebars. Different designs are used to unlock a tie bar. Principle reason is to permit installing molds that would occupy the complete platen minus the tie rod areas. Thus the mold literally has holes. Very popular are tiebarless systems which are also used. Without the tiebars, larger molds can reduce IMM cost, mount larger molds in a smaller IMM, permit quicker to easier mold mounting, no holes in molds, simpler part handling automation, etc.

Machine Control

Machine process controls coordinate individual functions of the clamp, injection unit, ejector mechanism, and mold systems and accessories such as core pulls and unscrewing dies for threaded parts. The more advanced controls employ a feedback system (closed loop) to provide much tighter control over actual parameters vs. setpoints. High-level controls are capable of communicating with auxiliary equipment such as chillers, hopper loaders, mold temperature controllers, robots, etc., and displaying all machine parameters and conditions (Chapter 3)

These never ending advanced controls allow interfacing many machines to a common host computer that allows plant-wide monitoring of the overall production status. The many software developments are rapidly changing the character of the molding machine.[3]

Machine startup/shutdown

For IMM startup experience provides a guide to setting plasticizer heat profile as well as other settings. Otherwise start with the plastic manufacturer's recommendations. There are different starting points for the various types of plastics that have to be interfaced with the different capabilities of IMMs to be used. The time and effort on startup make it possible to achieve maximum efficiency of performance vs. cost for the processed plastics. Information on process control settings developed can be stored and applied to future setups. Recognize that two identical IMMs usually require slight different settings to maximize their performance. Figure 4.5 provides examples of controls.

The term process control has often been used when machine control is actually performed. As the knowledge base of the fundamentals of the molding process continued to grow, the control approach is moving away from principally press control and closer to real process control where material response is monitored and then moderated or even managed (Chapter 3).

For startup mold setup is important. It includes:

1. determining plastic requirements based on type of mold to be used [cold runner (includes nozzle into cavity) or hot runner (only cavity)][183]
2. locate proper KO bars with all having equal lengths
3. select eyebolt hole which yields a level hang/lift
4. level mold and clamp to fixed platen
5. line up locating ring
6. slowly close mold
7. open moving platen and install KO bars if KOs are acting as pullbacks
8. tighten bars making certain they bottom out against the ejector plate
9. close platen
10. clamp mold to moving platen, remove safety straps, unhook hoist
11. open mold to desired daylight and set slowdown switches so that no high impact on the mold will occur
12. fine tune the final switch positions by repetitive small adjustments
13. connect all required power (electric, hydraulic, and/or pneumatic
14. check powered functions to ensure they are operating correctly such as electrical heaters just long enough to prove functionality avoiding excessive heat buildup before water is connected

15 connect water lines
16 turn water on (electric heaters off) and examine for leaks.[433]

Startup process control involves the machine operation and behavior of the plastic. Most important is the interaction between the machine operation and plastic behavior from the plasticator into the mold cavity(s). Principally the processing pressure and temperature vs. time determine the quality of the molded product. The design of the control system has to take into consideration the logical sequence of all these basic functions. They include injection speed (pressure dependent), clamping and opening the mold, opening and closing of actuating devices, barrel temperature profile, melt temperature, mold temperature, cavity pressure,[184] holding pressure, and mold cooling rate. These controls are essential to produce molded quality products and minimize cycle time. Quality features include mechanical properties, dimensional accuracy, absence of distortion, and surface quality.

Molding a product (part) involves the three stages of fill, pack, and hold. The following guide provides a simplified example for IM plastics.

1 Start with the plastic melt temperature at the mid-point of your supplier's recommended range. Know the actual melt temperature (not the barrel temperature set points).

2 As with the melt, the mold temperature should be centered to the recommended range.

3 Fill the mold as fast as you can and as far as you can. Separate speed from pressure. (Peak pressure during fill should never reach the injection pressure set point).

4 Packing should be as slow as possible via separating speed from pressure. Priority for termination of pack is the same as fill. The ability to pack on velocity is dependent on the hydraulic and/or electric architecture of the machine. Few presses are able to do this, which requires the operator to pack on machine pressure. Unfortunately, a constant pressure applied to a variable like plastic leads to a product that varies.

5 Hold with enough pressure and time to prevent plastic melt discharge from the mold until the gate seals. Ideally, hold should be a zero velocity setting with whatever pressure needed being available.

6 The criteria for determining cooling time now occurs when the product can accept the force of ejection and does not distort (hold time is cooling time).

7 For the majority of plastic materials, you should always run with a cushion.

8 Back pressure and screw rpm should be minimized. The goal should be to plasticate to the shot limit just before the cooling timer times out.

9 Once the process has been optimized, plastic conditions should be recorded such as fill time, peak pressure at fill, cavity pressure,[184] melt temperature, mold temperature, melt flow rates, and gate seal time. Record all basic machines setpoints on the setup sheet such as the transfer time (fill time) and weight, overall cycle time, and total shot weight, part weight, % runner, etc.

Start molding short shots and gradually increase the shot size as the injection speed while watching for flash or burning. Short shots that exhibit flash and/or burns indicate problems with tooling. Processing around a tool problem is a temporary resolution at best. Goal is to fill the mold as fast as possible. An ideal approach would provide a product 95% filled using 90% of the maximum injection rate of the press to operate with maximum efficiency. With the cavity approximately 95% filled leave the shot limit alone and start to lower the cut-off position. This will allow completing the fill portion of the cycle and using the inertia of the ram to pack out the product. With certain hydraulic IM machines that use servo valve technology for injection speed and pressure, it is not possible to completely separate fill from pack. This is best accomplish on machines that use a dual valve system. Lower the cut-off position until the product cavity is packed out making sure that a melt cushion exists. It may be necessary to increase the speed setting on the last step, but packing should be done as slow as possible.

After completing the packing start adding hold pressure and time period. Pressure should be high enough to keep plastic from discharging and time adequate to allow the gate to freeze (melt solidifies). Gate seal time can be determined by looking at cavity pressure at the gate or by weighing the product without the runner. After hold time is complete, delay the start of screw rotation (or decompress before starting the screw) to allow the pressure ahead of the screw to decay. Once the optimum cooling time is determined, screw rpm should be adjusted to minimize residence time (Figure 4.6). Profiled backpressures are not recommended. The slower the screw is allowed to turn the better the mixing action. Look at the peak pressure reached during fill and set the system pressure about 10% higher than this peak pressure. Minimizing the time used to open the mold, eject the product, and close the mold.

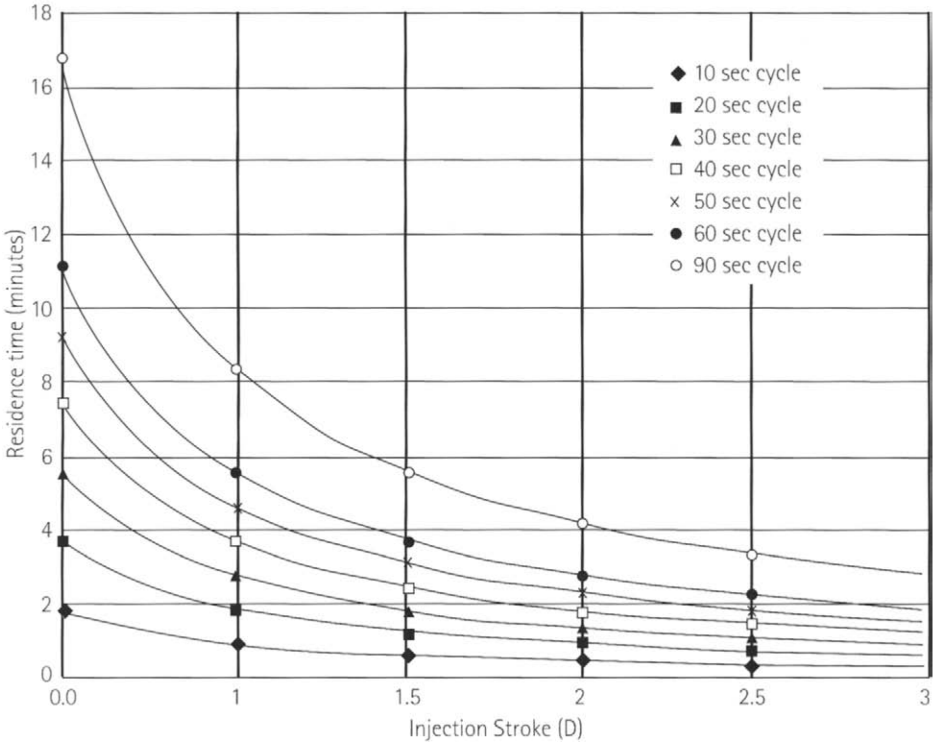


Figure 4.6 Plastic residence time

Summarizing and providing additional details to what has been reviewed follows. If required, purge barrel free of degraded resin. Set machine for semi-auto and start cycle; observe screw. Set barrel temperature profile based on experience or start with resin supplier recommendation. Determine or estimate the shot size[386] and set machine for approximately ⅔ of the mold's full shot. Set decompression stroke. Set a position transfer point (if machine is so equipped) approximately an inch from bottom. Set first stage pressure at 50% for starters and ultimately set at 100%. Estimate and set second stage time with pressure at zero. Set melt injection velocity to maximum. Adjust velocity and/or pressure as needed; if the fill was fast and short, the pressure can be increased. The fill pressure should be set high enough so the fill speed is not pressure limited, but controlled by velocity setpoints. Estimate and set cooling time. Set backpressure at 50 psi and gradually increase if necessary.

After observing each cycle, the shot size and transfer point will be adjusted frequently to set the process so that the first stage accomplishes 95 to 98% of the fill as measured by shot weight. Once the first stage shot size, transfer, velocity and pressure are set, we can set 2nd stage packing pressure. Adjust pack pressure as needed, but do not overpack. Recheck cushion. Some cushion should be maintained. Set screw speed so that recovery is completed just prior to next cycle, but not limiting cycle time. If flash occurs slow the velocity.

Maximizing Processing Window Control

For startups a processing window is determined that sets controls to fabricate acceptable products. It sets up the range of processing conditions such as melt temperature, pressure, shear rate, etc. within which a specific plastic can be fabricated with acceptable and optimum properties by a particular fabricating process. It is a defined area in a processing system process control pattern. This window for a specific plastic part can vary significantly if changes are made in its design and the fabricating equipment used.

Once the machine is operating, the processor uses a systematic methodical approach by making one change at a time, allowing the change to occur, and then to determine the result for each change. As an example by plotting at least injection pressure (ram pressure) with mold temperature, a molding area diagram (MAD) will provide the best combination of pressure and mold temperature necessary to produce quality parts (Figure 4.7). Developing this 2-D MAD approach ends up with a dramatic and easily comprehensive visual aid in analyzing variables. Within the diagram area, all parts meet performance requirements, however rejects could occur at the edges since material and machine capability are not perfect; variability exist (Chapter 1). By operating in the center of this diagram you are guaranteed to continuously mold acceptable products. If you desire to produce products at the lowest cost set the machine where maximum ram pressure and minimum mold temperature exists. However to compensate for potential variables that exists in machine and plastic performances (Chapter 1) carefully analyze molded products and if necessary reduce the settings to ensure acceptable products. Other controllable parameters can be added to target for improved quality such as melt temperatures (in the plasticator, nozzle, and in the cavity), rate of injection, etc.

A similar approach can be applied using three controls. Figure 4.8 presents a 3-D molding volume diagram (MVD) using injection ram pressure, mold temperature, and melt temperature. This approach simulates a processor's approach in startup of a machine when making additional control changes. After a 3-D MVD is constructed, it can be analyzed to find the best process settings of three combinations evaluated during startup. Note that a major cause for problems with

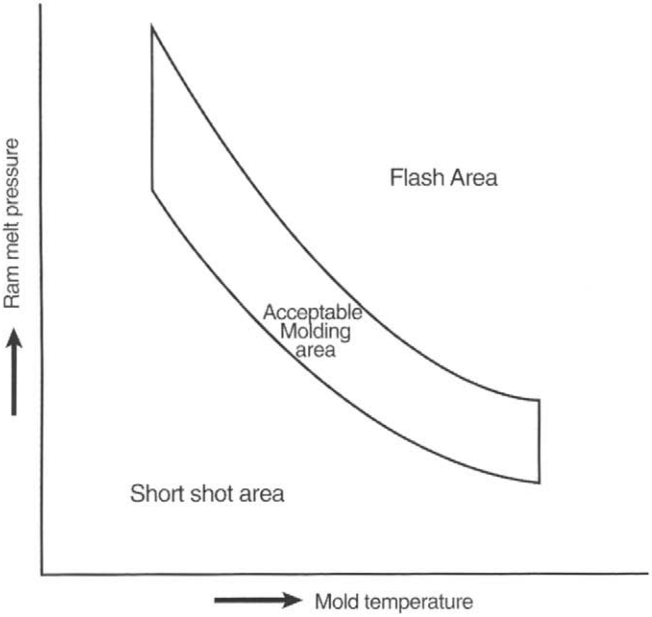

Ram melt pressure
Flash Area
Acceptable
Molding
area
Short shot area
Mold temperature

Figure 4.7 Molding area diagram processing window concept

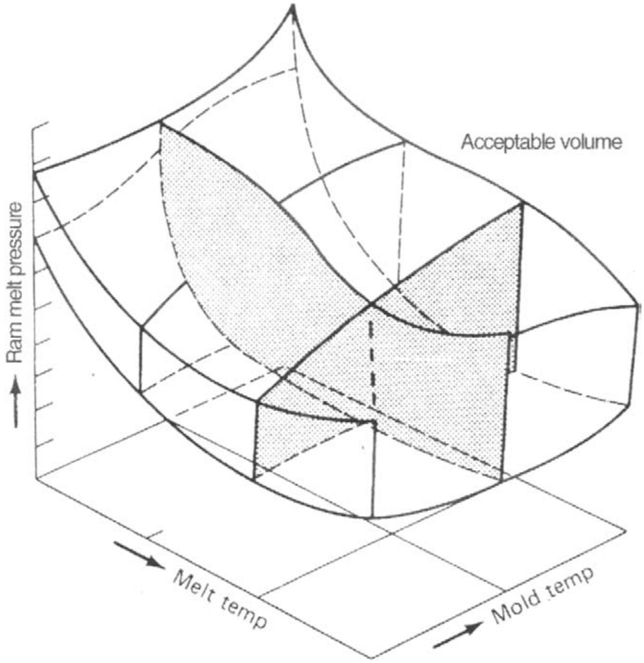

Acceptable volume
Ram melt pressure
Melt temp
Mold temp

Figure 4.8 Molding volume diagram processing window concept

any process is not of poor product design but instead that the processes operated outside of their required operating window.

Many different processing window studies are conducted. As an example an injection molded radar application requires critical controls for its parabolic form that has to be maintained through stringent application and environment conditions, while satisfying a number of other functional and quality requirements.[3, 4] A Design of Experiments (DOE) analysis was run to identify an optimal process window in the four-parameter design space, within which, ten very critical and tight-tolerance performance criteria are satisfied simultaneously. Prediction models generated based on the DOE analyses were shown to accurately represent the actual molding process. These models were then coded in a program to be utilized by molding engineers in process sensitivity analyses. Table 4.1 summarizes the results of the analysis for each of the performance criteria considered.[185]

Table 4.1 Processing window analysis

Quality Criteria	Spec/ Target	Critical Process Parameters	How the process parameters affect the quality criteria & other comments
Heat Deflection	<0.178 mm	Injection speed & hold time	Increasing hold time decreases Heat Deflection (HDT). Decreasing speed decreases HDT.
Foil quality at center	>2.5	Injection speed	Increasing speed decreases foil quality at center. Worst condition (=1) results in washing away of the foil in a 3.175 mm. to 3.429 mm. diameter at center.
Foil quality at edges	>2.5	Melt temperature, injection speed, hold pressure	Increasing any of these parameters increases foil quality at edges. The most effective is melt temperature, then injection speed, then hold pressure.
Tape test	>2.5	Melt temperature, injection speed, hold pressure, hold time	Increasing any one of these parameters increases tape test quality. Speed is by far the most effective, other three have approximately equal effect.
Thickness	1.98 mm to 2.02 mm.	Hold pressure and hold time	Measured at 2 locations, both about 25.4 mm. from the edge, 180° from each other. Increasing hold pressure increases the thickness. Second order dependence on hold time, with maximum thickness occurring at around 7.5 sec.
Parabola at 40.64 mm.	5.23 mm to 5.49 mm.	Melt temperature, and hold pressure	Increasing hold pressure or melt temperature increases this dimension; melt temperature somewhat more effective.
Parabola at 30.48 mm.	8.94 mm to 9.19 mm.	Melt temperature, and hold pressure.	Increasing hold pressure or melt temperature increases this dimension; melt temperature somewhat more effective.
Parabola at 20.32 mm.	11.58 mm to 11.84 mm.	Melt temperature, hold pressure, hold time, and injection speed	Increasing melt temperature or decreasing injection speed linearly increases this dimension. Dependence on hold time and hold pressure is quadratic; however, in the range of these parameters the team is most interested in (due to other criteria), increasing hold pressure or hold time increases this dimension.
Parabola at 10.16 mm.	13.18 mm to 13.44 mm.	Melt temperature, hold pressure, hold time, and injection speed	Injection speed and hold time are most effective with decreasing speed or increasing hold time increasing this dimension. Melt temperature and hold pressure has less of an effect with increasing temperature or decreasing hold pressure increasing parabola height at 10.16 mm.
Parabola at center	13.87 mm to 13.97 mm.	Melt temp., hold pressure, hold time, and injection speed	Same trends as above (for "parabola at 10.16 mm.) with, in this case, hold time having the biggest effect, followed by injection speed and hold pressure; melt temperature has the least effect.
Parabola Constant	193.92 mm to 195.92 mm.	Hold time, hold pressure, & injection speed	Increasing injection speed or hold pressure increases parabola constant; increasing hold time decreases it.

It lists the process parameters that affect each criterion and also describes the nature of the effect. As can be seen in this table, each of the performance criterions considered is affected by one or more of the four investigated process parameters. Furthermore, some of these effects are in terms of interactions of multiple process parameters (effect of one process parameter is dependent upon the value of another process parameter). This table points out that, for those performance criteria that are affected by multiple process parameters, the level of effect from each process parameter is different. For example, it is pointed out that foiling quality at edges of the part are affected by melt temperature, injection speed, and hold time. Then, the table further points out that melt temperature has the strongest effect on this performance criterion, injection speed has somewhat lesser effect, and that hold pressure has the least effect.

Processing window has been used to optimize the required uniform quality of optical components.[186] Part weight, dimensions, shrinkage and birefringence are a few important measurable parameters that are used to define the quality of plastic optical components. The quality of a plastic part can be assured by determining the proper and optimized set of injection molding process variables. Online cavity pressure data as a function of time for a dual cavity optical mold were analyzed for establishing the PVT (or PTv; pressure, temperature, volume) relationship. The PVT data were then used in an empirical model to determine the optimized set of process variables for the expected quality of a part (Figure 4.9).

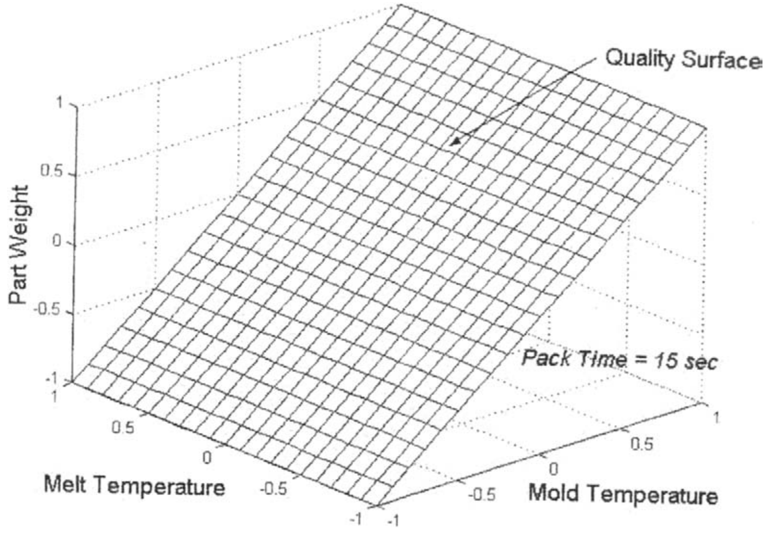


Figure 4.9 Quality surface as a function of process variables

Another example of a processing window study concerns thin-wall molding. In this study the effects of IM conditions and critical design parameters on the filling, dimensional stability, and crystallization of syndiotactic polystyrene (sPS) parts were studied.[187] Part wall thickness was the primary factor affecting filling, shrinkage, and crystallization. While injection velocity was secondary influence during, mold temperature was the minor factor for crystallization and shrinkage. Melt temperature and gate dimensions had little or no effect on filling or part properties.

In creating a process window for the combination of material, machine and heater used in this study, the first consideration was the moldability, which was dictated by the maximum injection pressure and the maximum clamp force. No changes in melt and mold temperature, injection velocity, or gate size could remedy this situation. Thus, an injection molding machine with higher injection speeds, pressures and clamp force was required to mold thin-walled syndiotactic polystyrene.

Crystallization and shrinkage were influenced by cooling rate (part thickness and mold temperature). While the oil-heated mold maximized crystallization, cooler (water-heatable) molds produced crystallinity levels of 25% or better (Chapter 1). Parts molded with the high mold temperature did exhibit better surface finishes. Shrinkage was relatively low for all processing conditions and design variables.

Coinjection molding

The review in coextrusion (Chapter 5) on advantages also applies with coinjection. Two or more injection molding barrels are basically joined together by a common manifold and nozzle through which melts flow before entering the mold cavity by a controlled device such as an open-closed valve system. The plastics can include the same material but with different colors. There are also systems sometimes used where one material with two shots is made from one plasticator whereby certain advantages develop vs. the usual single shot IM such as reducing pin holes, and/or strengthening the product. The nozzle is usually designed with a shutoff feature that allows only one melt to flow through at a controlled time. Other designs are used.[3, 29]

The usual coinjection with two or more different plastics is bonded or laminated together. Figure 4.10 shows the action where two or three plasticators can be used. With a two-system, one delivers melt to both sides of the part.

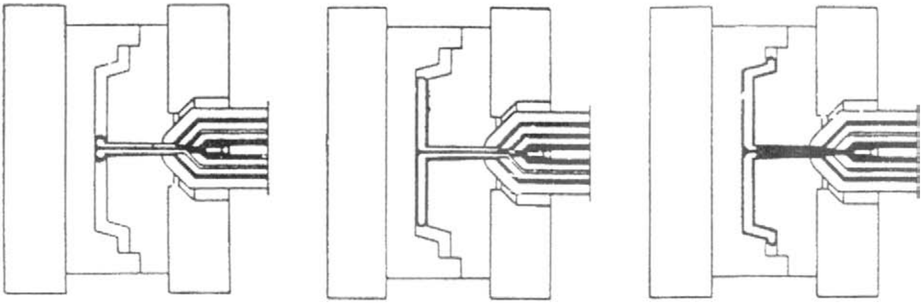


Figure 4.10 Example of a 3-layer coinjection system (courtesy of Battenfeld of America)

Proper melt flow and compatibility of the plastics is required in order to provide the proper adhesion. The type of the available plasticator and mold process control adjustments can compensate some of the melt flow variable factors.

Coinjection foam low pressure molding

Using the coinjection procedure, a solid melt is injected to form the solid, smooth skin against the cavity surface. Simultaneously a second short shot melt with blowing agent is injected to form the foamed core. With a full second shot, the mold can incorporate pins or a mold that opens similar to high-pressure foam molding.

Gas-assist molding

There are different gas-assist injection molding (GAIM) processes. Other names exist that include injection molding gas-assist (IMGA), gas injection molding (GIM), gas-injection molding machine (GIMM), or injection gas pressure (IGP). Most of the gas-assisted molding systems are patented. This review concerns the use of gas, however there are others such as water-assist injection molding. Most of the molding use thermoplastics but thermoset plastics can be used.[188]

The processes use an inert gas that is usually nitrogen with pressures up to 20 to 30 MPa (2,900 to 4,400 psi). Within the mold cavity the gas in the melt forms channels. Gas pressure is maintained through the cooling cycle. In effect the gas packs the plastic against the cavity wall. Gas can be injected through the center of the IMM nozzle as the melt travels to the cavity or it can be injected separately into the mold cavity.

In a properly designed tool run under the proper process conditions, the gas with its much lower viscosity than the melt remains isolated in the gas channels of the part without bleeding out into any thin-walled areas in the mold. The gas produces a balloon-like pressure on the melt.

The gas channels are those areas that have been thickened to achieve functional utility in the part or to promote better melt flow during cavity filling. This action provides a high degree of packing the melt against the cavity walls. Gas pressure is held until the melt solidifies. This coring action results in reducing cycle time and quantity of plastic used while developing a more structurally sound part (increases section stiffness), ability to improve surface flatness, reduce warps and sinks over thick sections, etc. Thick parts can easily be made without voids, sink marks, etc.

The gas-assist approach is a solution to many problems associated with conventional IM and structural foam molding (Chapter 8). It significantly reduces volume shrinkage that causes the sink marks in injection molding. Products are stiffer in bending and torsion than equivalent conventional IM products of the same weight. The process is very effective in different size and shapes products, especially the larger, longer, thick molded products. It offers a way to mold products with only 10 to 15% of the clamp tonnage that would be necessary in conventional injection molding.

The mold is designed for optimum material flow and gating. It is also designed for gas (or water, if used) injection and venting. The mold must also have shut-offs for the gas (and water), and another shut-off valve for the overflow.

Gas-assist without gas channel molding

The Battenfeld Airmould Contour process provides a gas-assist alternative when it is not possible to inject gas directly into the molten plastic, or where moldings with gas channel openings are not desirable. It can be used where parts only require one smooth or high gloss surface with different wall thickness or complex geometry on the other side. The process has gas entering between the melt and mold cavity surface where external pressure is applied to the melt. The gas can be applied within specific part sections.

Gas counterflow molding

A conventional IM system is used with a separate entrance to the mold cavity providing pressurized gas (usually nitrogen) prior to injecting the melt shot. This backpressure action can provide an even distribution of melt packing during its cooling cycle. When producing foamed plastic parts, this gas back pressure prevents the blowing agent from expanding until its part skin forms, followed by release of (venting) the gas pressure. Controlled foam expansion is provided.

Water-assist molding

A take-off of gas-assist is water-assist. To a degree, water injection molding will compete with gas-assist molding. Instead of gas, water is used to mold plastic into a hollow, thick-walled part, whereby the interior plastic of the part is cored out by water instead of gas. This action forces the surrounding plastic into contact with the mold walls as well as assisting in the cooling phase of the molding cycle. Its first stage is the complete filling and packing of the part. This typically means that the gate must be located on one end of the part, with a means to positively close after plastic injection.[189–192]

Materials used in the mold must resist corrosion. This makes stainless steel and copper alloys the materials of choice for water injection molds. The mold is designed with an overflow to provide positive control material flow at the opposite end of the cavity. When the main cavity has been filled, the valve to the overflow is opened and the injection of the secondary material takes place. At this point in the cycle, a gas (typically nitrogen) might be injected to core out the hollow feature and force the displaced plastic into the overflow. If a gas is used, then water injection follows. If not, water injection only occurs. Following water injection, another gas or even plain air is used to discharge the water from the part.

The water-assist molding, or water injection technology (WIT) originated in Aachen, Germany at the IKV (Institute for Plastics Processing). It requires a basic process requirement of high flow rates through the water injector into the part. This is much more critical than in gas-assist molding or gas injection molding (GIM) where a smaller amount of gas is delivered under pressure and expands outside the injector. The injector is the most crucial link between the WIT operation and the mold. To date about 90% of all problems in WIT can be attributed to the water injection nozzles.[142]

The IKV has developed several injectors. The simplest opens and closes under the pressure of the water. It is compact and easy to retrofit to gas-assist molds. But it does not allow water to be expelled from the part after molding, and there are reportedly some reliability problems. Other injectors, for series production, are operated externally. Water can pass both ways, so parts can be drained in the mold and the injectors are said to be more reliable. But they take up more space and, thus, are only appropriate for molds designed for WIT. IKV is working on optimizing the scaling effect around the water outlet and improving water retrieval during the molding cycle.

Injection-compression molding

Also called I-CM, coining, or injection stamping. It produces molded products with virtually no internal stresses and ease of meeting very tight tolerances. Instead of using the conventional IM mold with its two-halves meeting face to face, it uses a compression designed mold (Chapter 14) with a male plug fitting into a male cavity.

The essential difference in using these molds lies in the manner in which the thermal contraction in the mold cavity occurs during cooling (shrinkage). With conventional injection molding, the reduction in material volume in the cavity due to thermal contraction is compensated basically by forcing in more melt during the pressure-holding phase. By contrast with compression mold a full shot size enters the pre-opened-closed cavity mold but does not completely fill the cavity (Figure 4.11). The mold closes subjecting the melt to a relatively even melt flow. Required pressure is applied providing a molded part without stresses. This type molding has many advantages in favor of molded part performances.[4, 296]

Different products have been I-CM. A recent example is the cost-effective means of producing large side and rear automotive windows from polycarbonate (PC). This product was demonstrated by Battenfeld Injection Molding Technology of Germany (U.S. office in West Warwick, RI). It can deliver a 40% to 50% weight reduction compared to glass. The window project was a joint effort with Summerer Technologies, a German maker of in-mold decorating and laser-cutting systems, and Exatec, a joint venture of Bayer AG and GE Plastics. Exatec makes a scratch-resistant plasma surface coating for PC windows.

The PC window will be produced in a production cell comprising a 2420-ton Battenfeld HM two-platen press and an ABB jointed-arm

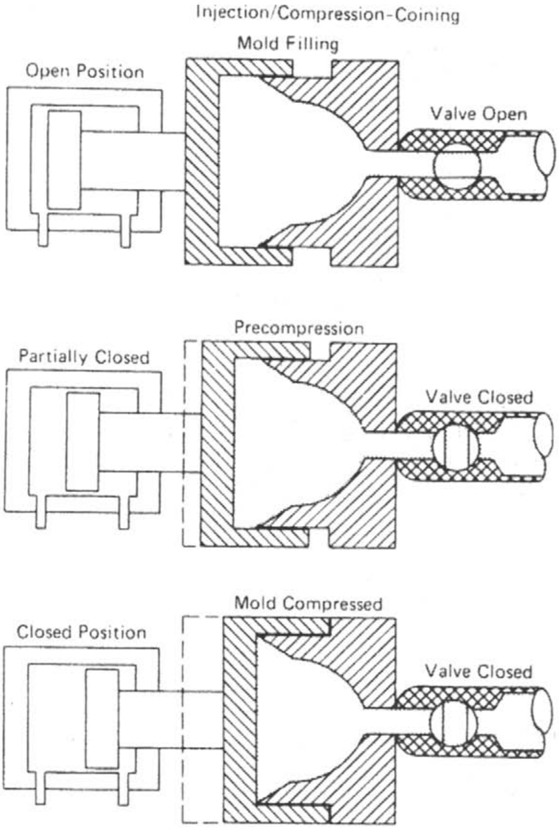

Injection/Compression-Coining
Mold Filling
Open Position
Valve Open
Precompression
Partially Closed
Valve Closed
Mold Compressed
Closed Position
Valve Closed

Figure 4.11 Example of mold action during injection-compression (courtesy of Plastic FALLO)

robot. It will use a new injection-compression process and a special mold technology – Battenfeld's process molds thin-wall products with long melt flow distances at low clamping forces and low molded-in stresses (800 248-6015, www.sms-k.com).

Two-shot molding/Over-molding

Two materials are molded so that the first molded shot is over-molded by the second molded shot; first molded part is positioned so the second material can be molded around, over, sections, or through it. The two materials can be the same or different and they can be molded to bond together or not bond together. If materials are not compatible, the materials will not bond so that a product such as a universal or ball-and-socket joint can be molded in one operation. If they are compatible, controlling the processing temperature can eliminate bonding. A temperature drop at the contact surfaces can occur in relation to the second hot melt shot to prevent the bond.[193]

In-mold molding

It involves the decorating of the plastic part while it is in the process of being molded (also called back molding). Performing operations such as decorative material, assembly, painting, labeling, printed film or foil, and/or lamination in the mold usually can result in cost savings compared to post-mold operations. Some part designs require materials that do not share any adhesive properties. In these cases, in-mold assembly not only allows use of such incompatible materials but also facilitates molding parts with movable joints in a single fabricating step. With plastic labeling, that includes thermoformed film and decorative material, there is usually the possibility of adding strength to the product so that a thinner wall is molded. In-mold can result in cost savings compared to post-mold operations.

Insert molding

Also called overmolding or molded insert. Process by which components such as pins, studs, terminals, and fasteners may be molded in a part to eliminate cost of post molding using rigid and/or flexible (soft) plastics. Molding flexible plastics such as TPEs over metal and/or rigid plastics has been extensively used providing benefits such as providing a flexible grip, soft-grip, and product aesthetics/visually appealing. However, considerable stresses can be set up in thermoplastic parts. To relieve stresses, design mold to meet plastic melt flow requirements and allow molded parts to cool slowly during molding and/or provide for oven cooling or annealing after molded. Other considerations to examine are:

1 Material compatibility: Chemical reactions can occur between the different materials that affect their adhesion where one plastic will eventually begin to peel away from the other.

2 Consistent insert tolerances: Any inconsistencies with the size and shape of the inserts will adversely affect the end product. With machined steel or metal inserts, any variation in their dimensions will affect how they are seated in the mold prior to plastic injection. Prior to molding over plastics allow the plastic to be covered, this meets its final dimensions after sufficient cooling (may take up to several days).

Thin-wall molding

As reviewed in this chapter demands have existed to create smaller, lighter thin-wall products. Thickness of thin-wall varies depending on the product such as electronics is at 1 mm and large automotive walls at 2 mm. Conventional melt delivery systems are usually not well suited for thin wall molding. This is particularly true using a hot runner system with engineering plastics. Extremely high injection pressures, properly controlled cavity fill speed at the start of fill, and stringent gate quality requirements associated with these applications require a specialized melt delivery. As an example without high pressures and uniform high heat at the gate(s), melt tends to freeze at the gate(s). Pressure changes occur with fill rates; faster fill tends to produce parts with lower pressure gradients from the gate(s) to the last area to fill in the cavity.

Thermoplastics have non-Newtonian melt flow characteristics; it means that their viscosity will change dependent on their velocity or the amount of shear that occurs in the melt (Chapter 1). This non-Newtonian characteristic is a key in thin wall molding. As in any molding setup one cannot just simply ram the melt into the cavity. It's flow characteristic, gate size as well as position, and venting have to be balanced in order to obtain the desired structural part and meet tight tolerance requirements.

There are computer programs that are successfully used that provide 3-D simulation of thin-wall IM products. An example is CAE using a 3-D Timon (Japan) software. The model used in this simulation was a speaker grille that had thin walls and many tiny openings (net), for sound to pass through them. These openings cause unfavorable weld lines. Effects on weld lines and effects of the number and location of gates were reviewed. This study resulted in using shorter flow length to thickness ratio which resulted in more stable filling and more uniform temperature distribution along the product. A multi-gating system makes weld lines more favorable than a single gating system.[194]

Soluble core molding

The soluble core technology (SCT) is also called soluble fusible metal core technology (FMCT), fusible core, lost-core, and lost-wax techniques. In this process, a core [usually molded of a low melting alloy (eutectic mixture) but can also use water soluble TPs, wax formulations, etc.] is inserted into a mold such as an injection molding mold.[3, 4] This core can be of thin wall or solid construction. If the part design permits, it can be supported by the mold halves or spider type pin supports that are used to have it located within the cavity; during plastic molding, the pins will melt. After the plastic solidifies, the core is removed by applying a temperature below the melting point of the plastic. Core material is poured through an existing opening which will require drilling a hole in the plastic. This technique is a take off and similar to the lost wax molding process used during the ancient Egyptian times for fabricating jewelry. Also the 1944 all plastic airplane used the lost wax process to bag mold its RP sandwich construction.[1]

Continuous molding

Machines to mold parts using continuously operating extruders (Chapter 5) have been designed, built, and used in different major production lines. The extruders are conventional types. They melt the plastic and have different techniques to deliver the melt into mold cavities. These continuously screw rotating machines use many molds. The molds are usually located on a rotating circular platform that can operate as Ferris wheels or carousels. Feeding a melt (through special nozzle adapters to the contour of the molds) onto a rotating mold is not new. Products made include shoe soles, shoe sandals, boats, Velcro strips, electrical male and female mini-connectors and/or photographic film containers.

Tandem machine molding

When a large enough IMM is not available and/or limited production exists, two IMMs side-by-side can operate in tandem. A large mold is located across both sets of platens.

Micromolding

Micromolding is precision molding of extremely small parts and components usually in engineering plastics unfilled, filled, and/or reinforced. Parts usually weigh less than 20 milligrams (0.020 g), with some even less that 0.1 mg in products as small as one mm^3. Products are measured in microns and have tolerances of ±10 microns or less. A micron (μm) is one-millionth of a meter; 25.4 μm make up one-thousandth of an inch. In comparison a human hair is 50 to 100 µm in diameter. A mil, that is about 25 times smaller than a micron, is one-thousandth of an inch.[444]

To date no standard definition has been adopted. Some refer to as anything smaller than a single plastic pellet or weighing less than a tenth of a gram even though micromolding technology can do better by turning out parts just a few ten thousandths of an inch thick and weighing less than a thousandth of a gram. Micromolders predict that demand and technology will continue to drive down part sizes probably to the point where molds can not be used for molding. New processing technology is being used to ensure that the right amount of plastic enters the mold.[476]

Molding small parts requires material moving in and out of cavities fast so degradation does not occur, etc. IMMs operate at very high injection pressures. Cycle times typically are about 1 to 8 s. Parts are produced with zero flash. They usually mold in multi-stage vertical or horizontal specialty IMMs (plasticating slanted screw, vertical dosing unit, horizontal injection plunger, etc.).

IMMs have been used in a clean room molding 0.8 mg acetal watch gears, 2 mg PC housing for hearing-aid in-plant, 16 mg glass reinforced LCP automotive micro-switch actuator pin, etc. Care has to be taken in handling parts. Some parts are so small and lightweight that static electricity can make them float in the air.

To obtain proper filling of micro structured parts significant modifications to the standard process is made. Due to the extremely low surface roughness of the mold cavity walls, demolding without a standard draft of 3° becomes feasible. However, during demolding any lateral offset has to be avoided. Otherwise it can be observed, that structures are ripped or sheared off the ground plate. To support the filling of small cavities, especially with a high aspect ratio (height against smallest lateral dimension) the so-called variothermal heating is used.[195]

In contrast to standard cooling, which keeps the mold temperature at a certain temperature below transition temperature, the surface of the mold is heated up with the help of an inductive heating almost to the melt temperature in order to gain a lower melt viscosity during filling. Compressed air causes problems. So the air in the mold must be evacuated by a vacuum pump. This is necessary to provide complete part filling as well as to prevent the burning of plastic by the compressed, hot air at the bottom of the cavity.

Molding machines and tooling for small parts are not just smaller versions of their regular larger molding counterparts. IM in micron sizes can be performed in special designed IMMs and molds.[38, 150] Some micromolders use screw-and-barrel molding machines similar to conventional machines except that the components are much smaller. There are plasticators (screw-and-barrel injection systems) with diameters that range from 14 to 20 mm and nozzle orifices of 1.5 mm.

To mold micron-scale precision parts with shot weights of only 0.0022 g, electrical operating IMMs are being used. Those who desire precise shot size (dosing) can buy electric injection machines with servomotors capable of very accurate screw positioning. With hydraulic IMMs, molders can install a valve gate that shuts when the correct amount of plastic has been injected into the mold.

Precision molding involves proper process control particularly high-speed injection speed and extremely low residence time. Proper venting usually has to include precision venting in the cavity as well as possibly removing air prior to entering the cavity. Product handling has to be considered. Approaches used include floating air systems, parts placed on film carriers, molded-in carrier strip made of the same material followed with automated separation, etc.

The ideal type of plastics to process are those with high melt flow indexes, low viscosity at processing temperatures, and consistent melt flow from one lot to the next from a material supplier. Reinforced plastics can set up problems such as meeting dimensions and/or tolerances and damage to molds.

Though material costs are usually negligible, to date the cost of specialized machines, molds, and secondary equipment makes micromolding an expensive process when compared to larger fabricated products.

To manufacture microparts less than a gram such as 0.0008g, the molding industry depends on new designs of IMMs, molds, and part-handling systems. The key to molding on this scale is getting the right amount of plastic into the mold. When molders do not accurately dose their shots, they risk overpacking their parts, which can cause the parts to stick in the mold, flash, and/or destroy itself.

A new option for micromolders is an injection machine that replaces the traditional screw with a motor-driven plunger. Named for the part sizes it produces, the Sesame is a small electropneumatic micromolding machine made by Hull Corp. (Warminster, PA). The machine can mold 20 thermoplastic "sesame seeds" from a single pellet. Instead of a screwing action, the Sesame uses a tiny plunger to push material into the mold. This plunger, that can be as small as 1.5 mm in diameter, is driven by an electric servomotor. To ensure accurate shot sizes, the servomotor can control plunger positions to within 5 mm. Total injection time can be as quick as 0.020 s. (Medical Murray Inc., Buffalo Grove, IL developed the Sesame technology and has licensed it to Hull.)

To keep plastic flowing through its small passages, the Sesame relies on a combination of high injection pressures (up to 50,000 psi) and high melt temperatures. High temperatures degrade materials during the time they spend in a conventional machine, but the Sesame is designed to minimize residence time. Material is in the Sesame for only a couple of minutes, compared to a couple of hours in a regular IMM. What accounts for the difference in residence times is that the Sesame holds an extremely small amount of material, far less than the smallest screw-and-barrel machine. A short screw would hold 20 times more material than the Sesame. The less material there is to heat, the shorter the required residence time.

A conventional method for removing material from a machine before it degrades is by using a large runner and sprue. Sometimes the runner and sprue are so large that the part material makes up less than 1% of the shot. That means that more than 99% of the shot material is wasted. Worse, the manufacturer loses control of the part-molding process. What is occurring is molding the sprue and runner with the part becoming a kind of by-product.

The Sesame is designed so that molders can use a smaller runner and sprue, which gives them more control over the amount of plastic and pressure used to form the part itself. A smaller runner and sprue also means less material waste. While screw-and-barrel systems waste as much as 99.7% of the shot material, the Sesame wastes less than 80%. This is particularly important when molding expensive materials like biodegradable plastics, which cost as much as $10 per gram. The Sesame can handle any type of moldable plastic, as well as silicone rubber. Super-small medical parts that have been molded by the machine include:

1 polyethylene medical catheter tips with a volume of 0.16 mm^3
2 0.0001g thermoplastic elastomer tubes for a microsurgery device,
3 medical silicone rubber tear-duct plugs with an outside diameter of 0.61 mm.

Future technology ideas enter the technology forming where the basic polymer raw materials would be inserted into a mold. Different monomers could be separately injected into a mold, where they would be subjected to form polymers (Chapter 1). There is also the concept of using several lasers into a box of gas. At the point where the laser beams intersect, the energy would produce a reaction that causes a part to form without a mold.[150]

Monosandwich molding

Two-component injection machines, using separate injection units for each of the two components perform the standard sandwich molding process. This process is characterized by a sequential injection of the two components using the same gating system. After filling the mold partially with the skin material with one injection unit the core component will be injected by the second injection unit. In order to avoid flow marks on the part surface a simultaneous phase is inserted between the injection of skin and core components. The final packing phase may be performed either with the core or the skin component.

In 1992, a new sandwich injection molding concept, called monosandwich, was developed by Jaroschek and Thoma (Ferromatic Milacron). In contrast to the standard sandwich molding process, this technology uses only one injection unit for both skin and core components with an extruder.

The cycle starts with the plastification of the core component in the injection unit. Then the extruder moves to the bottom position, the injection unit moves forward to the extruder nozzle to link the nozzles of the extruder and the injection unit. The extruder starts plastification of the skin component and extrudes the melted skin component into the screw antechamber of the injection unit. Thus the skin and core components are located one after the other in the screw antechamber. After the extruder moved back to the top position, the injection unit moves forward to the mold followed by a conventional filling phase. Due to the fountain flow effect the first injected material forms the skin layer followed by the second component forming the core. Compared to the standard sandwich process the injection phase of the monosandwich process is less complicated as it is identical to the conventional injection molding process.

Double-daylight molding

Combines hydroelastic metal forming on the moving platen and a hot runner injection molding (IM) system on the fixed platen (Arburg

GmbH). A center mold plate separates the two processes and is supported by guide arms on the tiebars. During processing a robot loads a metal blank into the hydroform section and moves the shaped blank from the previous cycle to the IM side. The molds closing action drives the hydro-forming process, and the already shaped blank is overmolded with plastics.

Foamed gas counter pressure molding

An airtight sealed mold can be pressurized to 400 to 500 psi (2.8 to 3.5 MPa) with an inert gas, usually N_2, or enough pressure to suppress foaming as the plastic mix enters the cavity. After the measured shot is injected, pressure is released allowing the instantaneous foaming to form a core between the already formed solid skins. A conventional IM system is used with a separate entrance to the mold cavity providing gas pressurization prior to injecting the melt shot. This back-pressure action can provide an even distribution of melt packing during its cooling cycle. When producing foamed plastic parts, this gas back pressure prevents the blowing agent from expanding until its part skin forms followed with releasing (venting) the gas pressure. Controlled foam expansion is provided.

High pressure foam molding

The plastic mix is injected into the mold creating a cavity pressure higher than the blowing agent gas pressure; usually much higher ranging from 5,000 to 20,000 psi (34.5 to 138 MPa). As soon as the part skin surface hardens to the desired thickness, cavity melt pressure is reduced to produce a foamed core. Different techniques are used to release pressure such as withdrawing core pins in the cavity or by special press motions that partially open the mold halves using 2-D or 3-D motions (Chapter 8).

Low pressure foam molding

Low pressure or short shot conventional IM are the most commonly used because they are easy and simple to operate. Suited for economical production particularly of large, complex, 3-D parts. Usual cavity pressure is 200 to 500 psi (1.4 to 3.5 MPa). An accumulator can be used between the plasticator and mold providing a means of injecting a very large shot. Since low pressures are used, the parts surface appearance does not approach those processes using the higher pressures. Attractive surface patterns can be molded such as swirls.

Liquid molding

Also could be called reaction injection molding (Chapter 12). This LIM (liquid injection molding) process involves proportioning, mixing, and dispensing two liquid plastic formulations. This compound is directed into a closed mold. It can be used for encapsulating electrical and electronic devices, decorative ornaments, medical devices, auto parts, etc. It uses a mechanical mixing rather than a RIM high-pressure impingement mixer. Flushing the mix at the end of a run is easily handled automatically. Plastics used include silicones, acrylics, etc. To avoid liquid injection hardware from becoming plugged with plastics, consider using a spring-loaded pin type nozzle. The spring loading allows you to set the pressure so that it is higher than the pressure inside the extruder barrel, thus keeping the port clean and open.

Counterflow molding

It is used to eliminate or reduce weld lines. Two separate injectors or one injector with a splitting device are used to move melt in and out of the cavity from opposite sizes. This type action repeats and is programmed to maximize the best melt flow patterns.

Melt flow oscillation molding

Scorim Process or SP (Cinpres-Scorim), Rheomolding Process or RP (Thermold's), and the Press Alpha Process or PAP (Sumitomo Heavy Industries and Sankyo Chemical Engineering of Japan) processes are examples of this method. The SP multi-live feed molding process where two packing pistons oscillate 180° out of phase and eliminate weld lines, etc. The RP system provides 3-D orientation based on the concept of melt rheology as a function of vibration frequency and amplitude as well as temperature and pressure. The equipment utilizes piston/type melt accumulators set up adjacent to the melt stream of the plasticator. Piston oscillates back and forth. The PAP system uses compression pins that are actuated when the cavity fills. These pins protrude into the cavity and begin oscillating to create localized compressions. Action eliminates weld lines, sinks, and warpage, reduces filling pressures, localized thin wall molding, and allow for gate positioning flexibility.

Screwless molding

Practically all IMMs worldwide use screws to melt plastics. However the original designed ram hydraulic IMM type (screwless) of over a century ago has limited use (Figure 4.12). This ram IMM can process certain plastics with very little or no melt flow capability that a screw system cannot. Ultrahigh molecular weight polyethylene (UHMWPE) with its rather exceptional superior properties such as exceptional wear resistance is ram injection molded (also compression press sintered or ram extruded). For long runs of fairly small products (2 to 300g) with complicated shapes, conventional screw injection molding can be used as long as one recognizes that this very highly viscous plastic can cause high pressure loss along the melt flow path through the plasticator. The molecular weight and end properties can be severely degraded by the screw.

Non-plastic molding

The processing methods go by different names such as metal injection molding (MIM), ceramic injection molding (CIM), powder injection molding (PIM), etc.[297–299, 464] They include aluminum, ceramics, concrete, copper, dynamite, food, magnesium, stainless steel, wood, zinc, tungsten carbide, and other alloys of metals. Most of the materials have been in very fine powdered form. These green materials have been used alone but usually with plastic binders (Figure 4.13).

Precision and complex parts have been molded that are usually small in size such as micro size. Micromolding requires more accuracy than macromolding. The green material can have a high bulk density of about 50 to 70 wt% of their solid counter material. Binders can be removed using heat, solvent, or their combinations to purge or remove most of the plastic. In turn the parts can be sintered in a vacuum furnace to fuse the metal particles. Fusing causes the parts to shrink isotropically to achieve a 95–99% density. It is interesting and factual that the first development of plastic IM was a take-off from the die casting machinery (using a much lower temperature melting pot that is higher than melting plastic).

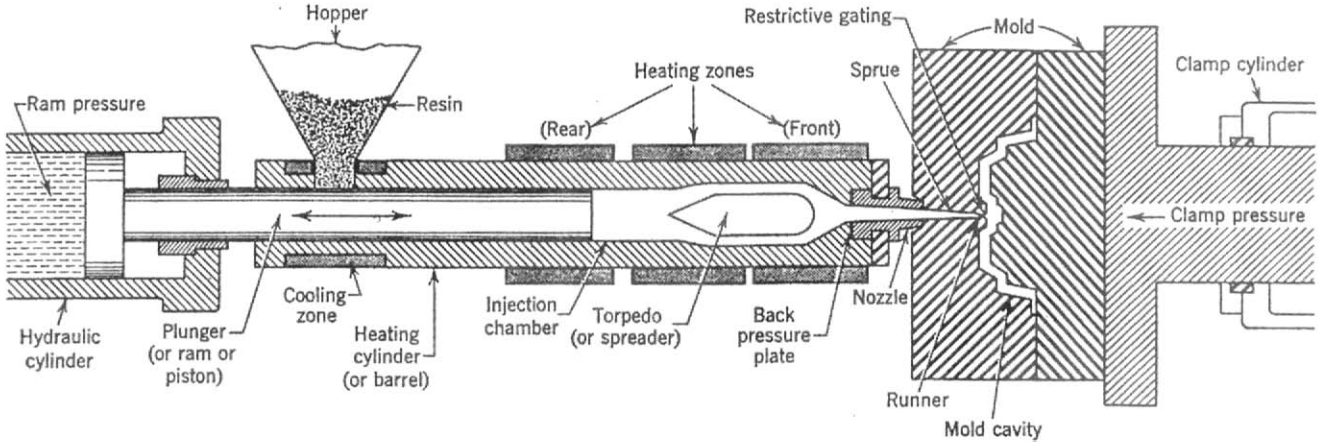

Hopper
Resin
Ram pressure
Heating zones
(Rear)
(Front)
Restrictive gating
Mold
Sprue
Clamp cylinder
Clamp pressure
Hydraulic cylinder
Plunger (or ram or piston)
Cooling zone
Heating cylinder (or barrel)
Injection chamber
Torpedo (or spreader)
Back pressure plate
Nozzle
Runner
Mold cavity

Figure 4.12 Schematic of a ram (plunger) injection molding machine

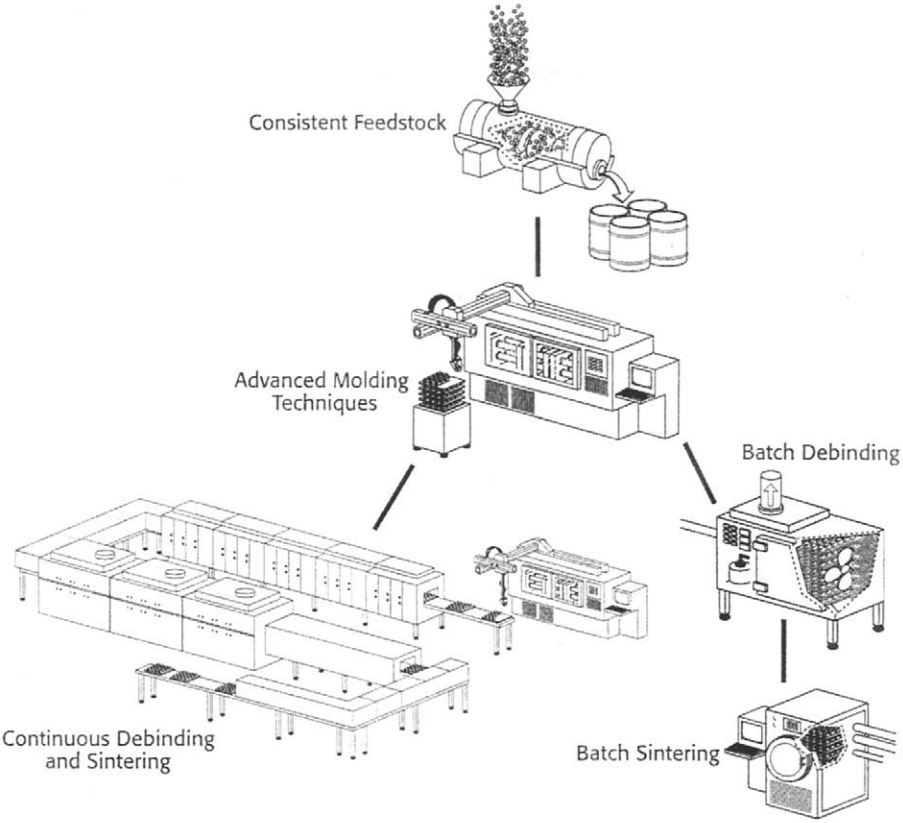

Consistent Feedstock
Advanced Molding Techniques
Batch Debinding
Continuous Debinding and Sintering
Batch Sintering

Figure 4.13 Metal injection molding cycle (courtesy of Phillips Plastics)

Magnesium molding

Japan Steel Works Ltd. (JSW), Hiroshima, Japan and Husky Injection Molding Systems Inc., Bolton, Ontario, Canada (licensee of Thixomat Inc., Ann Harbor, MI) design and manufacture Thixomolding presses worldwide for molding magnesium (Mg) particularly small moldings. These machines are based on using modified IMMs (Breger). New designs include providing much higher speed reciprocating screw action and higher heated barrel zones. For injection, Mg has to blow out a magnesium plug that is in a semi-solidified state. Due to its very high injection speed (compares to firing a cannon) the machine is subjected to very high shock and vibration requiring a much stronger machine then a plastic IMM.

Thixotropic molding

The patented thixotropic technology is called Thixomolding. Traditional die casting machines use a large pot of molten Mg that can be hazardous to workers and creates sludge that is foundry waste. By contrast thixotropic IMMs use chips of Mg similar to plastic pellets. All the heating (up to 1,200F) and melting is done in the barrel, totally enclosed and air-tight to keep oxygen away from the Mg which can catch on fire in its molten stage. The screw does not melt the Mg; it just conveys it forward and breaks up the jagged dendrites into round shapes that can be pushed into the mold with ease. Injection speeds can reach 3,000 mm/s. After each molding shot the mold cavity has to be sprayed with a mold release agent to eliminate the Mg fusing to the cavity.

Summary

As IM technology expands, requirements for precision injection molding machinery have followed suit. Profitable molding in today's highly technical and competitive world depends on precise clamping action coupled with both high plasticizing performance and reliability. This review has examined basic physical processes affecting the speed for productivity of an IMM. These are the processes that must occur in any IMM regardless of its specific design or of the refinements it contains in control systems or hydraulic circuitry.

Today, the actual IMs that may be found on the market come in a myriad of sizes and designs. Because it is possible to combine a variety of different sizes of injection or plasticating systems with almost as many different sizes of clamp systems, there is almost no limit to the number of combinations available considering both the domestic and foreign sources of equipment. However, in every case, each machine must provide the necessary facilities to melt the plastic, inject it, and cool it.

A glimpse of future IMMs has been introduced that will use laser and microwave plasticators, fiber-optics monitoring, quiet electromagnetic drives, voice-activated controls, permit quick plastic changes without purging, eliminate hoppers by storing plastics in modular tanks on the machine's bed and feeding by vacuum pumps behind the plasticators, and more innovations. Features to be gained include more energy savings, increase process efficiencies, simplify controls so that the IMMs will be easier to operate, and improve and provide repeatability of melts. This program called Mother Project was started in 1999 and targeted to be completed by 2017. Studies are being conducted by MIR, S.p.A, Italy in cooperation with the Univ. of Turin's Plasturgy Dept.; the USA agent is MIR USA, Leominster, MA.

5 EXTRUSION

Introduction

Extrusion is the process of heating practically only TPs that may be in the shape of powders, beads, flakes, pellets, or combinations of these forms. This plastic enters the extruder's hopper. The extruder utilizes a plasticator [spiral screw that rotates within a heated barrel (cylinder)] to melt the plastic (Chapter 3). The melted plastic is then forced through a die to produce the desired continuous product shape. Figure 5.1 shows a very simplified schematic of the extrusion process. Information on dies (mono-layer and coextruded) used in extrusion is in Chapter 17.

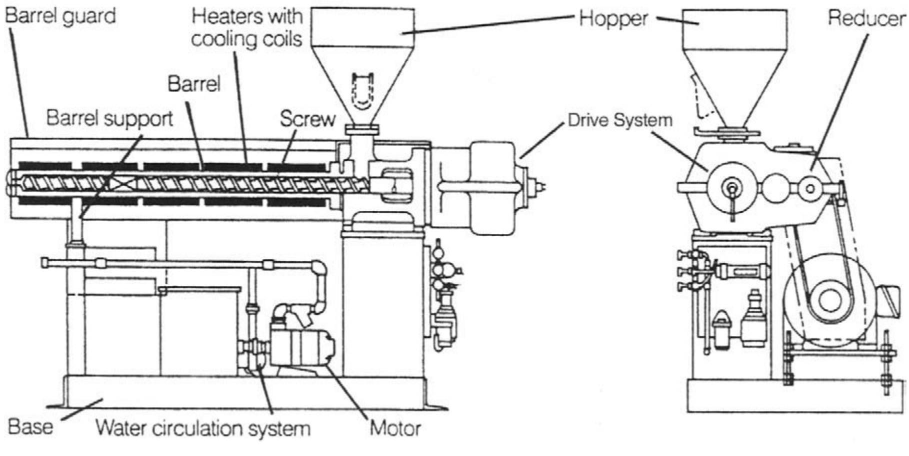

Barrel guard
Heaters with cooling coils
Barrel
Barrel support
Screw
Hopper
Reducer
Drive System
Base
Water circulation system
Motor

Figure 5.1 Simplified example of a single-screw extruder

Extrusion is the single most popular process for forming TPs. It processes over 36wt% of all plastics consumed worldwide into products such as ranging from rather simple films, sheets, rods, coatings to very complex profile forms used in window profiles, etc. Most of plastics used are polyethylene (PE) (Chapter 2).[451] Other plastics are used (Table 5.1). Unlike injection molding, the second major process consuming plastics (32wt%), extrusion usually results in a semi-finished or intermediate product. They require further processing to produce usable products.

In maximizing performance, or at least meeting performance requirements of extruded plastics as well as minimizing cost to extrude products it is important to understand the processing behavior of the different plastics. In producing the different extruded products certain plastics can be used. An understanding of factors such as their rheological to decomposition behaviors as well as problems that can develop provide information that will make it easier to extrude products (Chapters 1, 2, 3, and other chapters).

Downstream of the die, the extrudate (melt) is calibrated, cooled and packaged by an array of ancillary auxiliary devices including vacuum calibrators, water tanks, cooling rolls, haul-offs, cutters, and winders (Chapter 18). Upstream of the die, a melt pump may be interposed between the extruder and the die to produce a more uniform extrudate. The exact selection and arrangement of these component parts of an extrusion system will depend on the end product and tolerance requirements that have to be met.[25, 27, 33, 143, 196, 476]

On leaving the extruder, the extrudate (melt) is drawn by a pulling action or other device, at which stage it is subject to cooling, usually by water and/or blown air device. This is an important aspect of downstream control if tight dimensional requirements exist or conservation of plastics is desired. The processor's target is to determine the tolerance required for the pull rate and to see that the downstream equipment meet the total line requirements. Even if tight dimensional requirements are not required, the probability is that better control of the pull speed will permit tighter tolerances so that a reduction in the material's output will occur resulting in lower product cost.

By far practically all extruders use screws in their plasticators to melt the plastics. However ram, over a century popular melting system, is used to process plastics that cannot be melted by a screw. The ram devices are essentially batch devices, and although it is possible to achieve a constant output by sequentially operating two or more rams, the method is of virtually no importance for practically all TPs. The ram is used for processing plastics that come close to not being meltable. Another possibility is the rotary extruder, a device in which rotating

Table 5.1 Example of thermoplastics that are extruded (courtesy of Spirex)

Resin data[b]	*Specific gravity* ($g\,cm^{-3}$)	*Density* ($lb\,ft^{-3}$)	*Specific volume* ($in^3\,lb^{-1}$)	*Specific volume* ($cm^3\,g^{-1}$)	*Extrusion temperature* (°F)	*Specific heat* ($BTU\,lb^{-1}\,°F^{-1}$)	*Water absorption in 24 h* (%)	*Maximum water content allowable*
ABS, extrusion	1.02	64.0	27.0	0.980	435	0.34	0.25	
ABS, injection	1.05	65.0	26.0	0.952		0.40	0.40	0.20
Acetal, injection	1.41	88.0	19.7	0.709		0.35	0.25	
Acrylic, extrusion	1.19	74.3	23.3	0.839	375	0.35	0.30	
Acrylic, injection	1.16	72.0	24.1	0.868		0.35	0.20	0.08
CAB	1.20	74.6	23.1	0.833	380	0.35	1.50	0.15
Cellulose acetate, extrusion	1.28	80.2	21.6	0.781	380	0.40	2.50	
Cellulose acetate, injection	1.26	79.0	21.9	0.794		0.36	2.40	0.20
Cellulose proprionate, extrusion	1.22	76.1	22.7	0.821	380	0.40	1.70	
Cellulose proprionate, injection	1.22	75.5	22.9	0.828		0.40	2.00	0.25
CTFE	2.11	134.0	13.1	0.473		0.22	0.01	
FEP	2.11	134.0	12.9	0.465	600	0.28	<0.01	
Ionomer, extrusion	0.95	59.6	29.0	1.050	500	0.54	0.07	
Ionomer, injection	0.95	59.1	29.2	1.060		0.54	0.20	
Nylon-6	1.13	70.5	24.5	0.886	520	0.40	1.60	0.15
Nylon-6,6	1.14	71.2	24.3	0.878	510	0.40	1.50	0.15
Nylon-6,10	1.08	67.4	25.6	0.927		0.40	0.40	0.15
Nylon-6,12	1.07	66.8	25.9	0.935	475	0.40	0.40	0.20
Nylon-11	1.04	64.9	26.6	0.962	460	0.47	0.30	0.10
Nylon-12	1.02	63.7	27.1	0.980	450		0.25	0.10
Phenylene oxide based	1.08	67.5	25.6	0.926	480	0.32	0.07	
Polyallomer	0.90	56.2	30.7	1.110	405	0.50	0.01	
Polyarylene ether	1.06	66.2	30.7	0.940	460		0.10	
Polycarbonate	1.20	74.9	23.1	0.832	550	0.30	0.20	0.02
Polyester PBT	1.34	83.6	20.7	0.746			0.08	0.04
Polyester PET	1.31	8.18	21.1	0.746	480	0.40	0.10	0.005
HD polyethylene, extrusion	0.96	59.9	28.8	1.040	410		<0.01	
HD polyethylene, injection	0.95	59.3	29.1	1.050		480	<0.01	
HD polyethylene, blow molding	0.95	56.9	28.8	1.040	410		<0.01	
LD polyethylene, film	0.92	57.44	30.1	1.090	350		<0.01	
LD polyethylene, injection	0.92	57.4	30.1	1.090		400	<0.01	
LD polyethylene, wire	0.92	57.4	30.1	1.090	400		<0.01	
LD polyethylene, ext. coating	0.92	57.1	30.0	1.090	600		<0.01	
LLD polyethylene, extrusion	0.92	57.4	30.1	1.087	500			
LLD polyethylene, injection	0.93	58.0	29.8	1.075		425		
Polypropylene, extrusion	0.91	56.8	30.4	1.100	450		0.03	
Polypropylene, injection	0.90	56.2	30.7	1.110		490	<0.01	
Polystyrene, impact sheet	1.04	64.9	26.6	0.963	450		0.10	
Polystyrene, gp crystal	1.05	65.5	26.2	0.943	410	425	0.03	
Polystyrene, injection impact	1.04	64.9	26.6	0.968		440	0.10	
Polysulfone	1.25	77.4	22.3	0.807	650	680	0.30	0.05
Polyurethane	1.20	74.9	23.1	0.834	400	400	0.10	0.03
PVC, rigid profiles	1.39	86.6	19.9	0.720	365		0.02	
PVC, pipe	1.44	87.5	19.7	0.714	380		0.10	
PVC, rigid injection	1.29	83.6	21.0	0.756		380	0.10	0.07
PVC, flexible wire	1.37	85.5	20.2	0.731	365			
PVC, flexible extruded shapes	1.23	76.8	22.5	0.814	350			
PVC, flexible injection	1.29	80.5	21.4	0.776		300		
PTFE	2.16	134.8	12.9	0.464			<0.01	
SAN	1.08	67.4	25.6	0.927	420	470	0.03	0.02
TFE	1.70	106.1	16.3	0.589		610	0.01	
Urethane elastomers	0.83	51.6	33.5	1.210	390	400	0.07	0.03

[a] Specific information on all machine settings and plastic properties is initially acquired by using the resin supplier's data sheet on the particular compound or resin to be used.

[b] These are strictly typical average values for a resin class; consult your resin supplier for values and more accurate information.

discs or rotors are used to generate shear. However, TPs extrusion depends almost entirely on the rotating screw as a melt delivery device.[143, 476]

TPs are characterized by low thermal conductivity, high specific heat, and high melt viscosity. Preparation of a uniform homogeneous melt and its delivery at adequate pressure and a constant rate could pose considerable problems if not properly processed (Chapter 3). The principal extruder variants are the single-screw and the twin-screw types. Of these, the single-screw extruder is by far the most versatile and popular in use.

The single-screw extruder consists essentially of a screw that rotates in an axially fixed position within the close-fitting bore of a barrel. Extruder sizes are identified by the inside diameter of their barrel. Size range from ¼ to 24 in. diameter with the usual from 1 to 6 in. (Europe and Asia sizes range from 20 to 600 mm with the usual from 25 to 159 mm.). The screw is electrically motor driven through different devices such as a gear reduction train or belt to meet different performance and cost requirements. These gear reducers are rated in mechanical horsepower and thermal horsepower as defined by the American Gear Manufacturers (AGMA). The AGMA rating system is based on the understanding that not all gear reducers are used the same way. There are also gearless drive systems such as those using Siemens high-torque motor with an unusual low-inertia hollow shaft.[476]

The output rate of the extruder is a function of screw speed, screw geometry, and melt viscosity. The pressure developed in the extruder system is largely a function of die resistance and dependent on die geometry and melt viscosity. Extrusion pressures are lower than those encountered in injection molding. They are typically 500 to 5000 psi (3.5 to 35 MPa). In extreme cases, extrusion pressures may rise as high as 10,000 psi (69 MPa). Variants on the single screw include the barrier or melt extraction screw and the vented screw (Chapter 3).

The twin-screw extruder may have parallel or conical screws, and these screws may rotate in the same direction (co-rotating) or in opposite directions (contra-rotating). Extruders with more than two screws are known as the multiple-screw extruder. These extruders are normally used when mixing and homogenization of the melt is very important, in particular where additives, fillers, and/or reinforcements are to be included in the plastic.

They are extensively used for plastic compounding that includes heat-sensitive materials such as PVC, processing of difficult-to-feed materials (such as certain powders), reactive processing,[197] and for plastic devolatilization. Twin-screw extruders particularly offer a wide processing variability. They can be starve-fed so that residence time, amount of shear, and control of melt temperature can be controlled by means of their segmental modular designs.

Component

There are different components that make up the extruder each with their specific important function. All components have to operate efficiently otherwise the extruder's operation is inefficient. A very important and essential parameter in the extruder is the plasticator's pumping process. It is the interaction between the rotating flights of the screw and the stationary barrel wall. For the plastic material to be conveyed, its friction must be low at the screw surface but high at the barrel wall. If this basic criterion is not met, the plastic will usually rotate with the screw and not move in the axial output direction.

In the plasticators output zone, both screw and barrel surfaces are usually covered with the melt, and external forces between the melt and the screw channel walls have no influence except when processing extremely high viscosity plastics such as rigid PVC and UHMWPE. The flow of the melt in the output section is affected by the coefficient of internal friction (viscosity) particularly when the die offers a high resistance to the flow of the melt (Chapter 3). Figure 5.2 shows the extruder's components where the following identifications are listed:

1 Drive motor from 20 to 2000 hp infinitely variable speed drives directly coupled to reducer for maximum efficiency deigned to save floor space.

2 Gears and gearless to provide high efficiency capability to process plastics.[476]

3 Efficient performance heat treated helical or herringbones (gears equipped with shaft-driven oil pumps and oil cooler).

4 Thrust bearing with long life expectancy (of well in excess of 30 years' continuous operation).

5 Large rectangular standard feed opening (round with lining, optional, for use with crammer feeders).

6 Long lasting barrel heater/cooler elements that heat quickly.

7 Cooling tubes run parallel with heating elements. The cast-in stainless steel tubes closed-loop system provide non-ferrous distilled

water that is automatically adjusted via microprocessor-based temperature controllers providing uniform, efficient cooling.

8 High-performance screw with bimetallic lined cylinder designed for processing a specific plastic; can be cored for cooling.

9 Prepiped and prewired power installation.

10 Safety heat conservation and heat protection guards that are one-piece, hinged, no loose parts insulated.

11 Heavy single unit steel base machine foundation preassembled so all parts are in place ready to be used.

12.When required, patented two-stage vented plasticator is used (that can be plugged in minutes).

13 Screen changer for continuous operation without shut down using standard hinged swing-bolt gate.

14 Gear pump to ensure absolute volumetric output stability.

15 Static mixer to provide thermal and viscosity homogeneity.

16 Die designed to produce single or multi-layer sheet without modification; strand dies, etc.

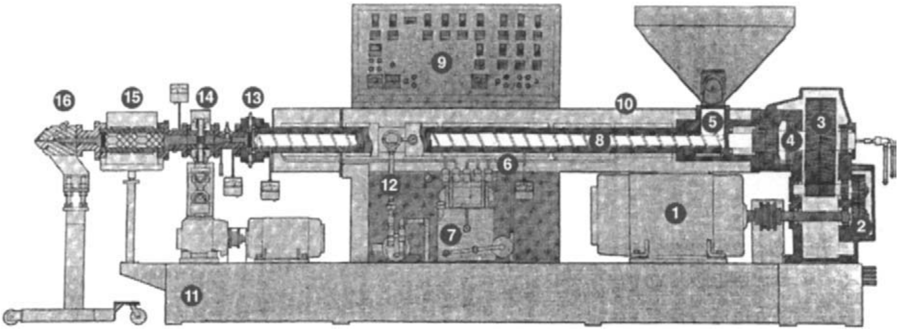


Figure 5.2 Schematic identifies the different components in an extruder (courtesy of Welex Inc.)

Purpose of the screens is primarily twofold: (1) to change the melt's spiraling motion, caused by the screw rotation; and (2) to filter contaminants out of the melt. Most plastics contain contaminants and these particles can be conveniently removed by means of a screen placed after the extruder barrel and before the melt flow reaches the extrusion die. The simplest means for filtering plastic melts are woven wire mesh disks of about the same diameter as that of the extruder barrels. Several layers of different screens are usually made up into one screen pack. The innermost layer is the finest mesh screen that determines the particle size that will be caught by the screen pack.

Against the forces exerted by the melt flow, the screen packs are backed by a thick, densely perforated steel disk called a breaker plate. The outer rims of the breaker plate and of the screen pack fit into a round recess in the end of the extruder barrel and are clamped in place by the adapter flange of the adjoining piece of equipment, usually that of the extrusion die. To change a clogged screen pack, the die adapter flange has to be removed, the old pack taken out and replaced with a new one, and the equipment reassembled.

Screen changers are mechanical devices that permit changing screens in a faster and more convenient way. Screen changers fall into three main categories: (1) manual, (2) intermittent (reciprocating), and (3) continuous screen changers. Other types of reciprocating screen changers employ valves by means of which the melt flow may be diverted from one screen pack to the other, and back again. The ever-changing pressure conditions that are inherent in all intermittently operating machines can be eliminated by the use of continuous screen changers.

If it is at all possible to do without screen packs they should not be used. Various reasons exist. Complete and continuing displacement of melt from all points in the screen pack is rather difficult. Hundreds of small dead spots are filled with melt as soon as the pack is put into service, and the material in these spots is moved only very slowly, if at all, by the drag of neighboring melts. This action can cause contaminating and degrading of the extrudate.

The gear pump is a component that has been standard equipment since the 1930s in textile fiber production. During the 1980s they established themselves in all kinds of extrusion lines. Gear pump is used to generate even melt pressure. Two counter-rotating gears transport a melt from the pump inlet (extruder output) to the pump discharge outlet. Gear rotation creates a suction that draws the melt into a gap between one tooth. This continuation action from tooth to tooth develops a surface drag that resists flow, so some inlet pressure is required to fill the cavity.[492]

Static mixer, also called a motionless mixer, provides a homogeneous mix by flowing one or more plastic streams through geometric patterns formed by mechanical elements in a tubular tube or barrel. These elements cause the plastic compound to subdivide and recombine in order to increase the homogeneity and temperature uniformity of the melt. There are no moving parts and only a small increase in the energy is needed to overcome the resistance of the mechanical baffles. These mixers are located at the end of the screw or before the screen changer or between the screw and gear pump.

The temperature profile required along a barrel, adapter, and die depends largely on the specific extrusion process line with its screw design, plastic used, and available process control (Chapter 3). The thermal condition of the plastic is essentially determined for a given material by screw geometry with its rotational speed and the total restriction or pressure existing in the die. The electrical heaters are normally placed along the barrel grouped in separate and adjoining zones; each zone is controlled independently. Small machines usually have two to four zones. Larger machines have five to ten zones. Table 5.2 provides information on the different types of heater bands.

Table 5.2 Selection guide for barrel heater bands (courtesy of Spirex)

STYLE	INSULATION	MAX. TEMP.	MAX. WSI	ADVANTAGES	DRAWBACKS
Mica	Plate Mica	900 F	50	Low cost, Versatile	Low temperature
Ceramic	Cordierite Steatite Silicon Carbide	1400 F	50	High temperature, Flexible, Energy efficient	Prone to contaminants
Mineral Insulated	MGO	1400 F	230	High temperature, Response time	Cost, Versatility, Energy efficiency
Tubular	MGO	1200 F	100	Durability	Energy efficiency
Cast Aluminum	MGO	650 F	35	Uniform heat	Cost, Low temperature
Cast Water Cooled	MGO	650 F	35	Efficient cooling	Cost, Water leaks, Scaling
Cast Air Cooled	MGO	650 F	35	Durability, Cost	Cost
Ceramic Air Cooled	Steatite	1200 F	50	Cost, High temperature	Cooling, Efficiency

MGO = magnesium oxide

Information on dies and process control is in Chapter 3. Different control systems are used to process the different extruded products. Simplified examples of different controls are provided in Figures 5.3 and 5.4.

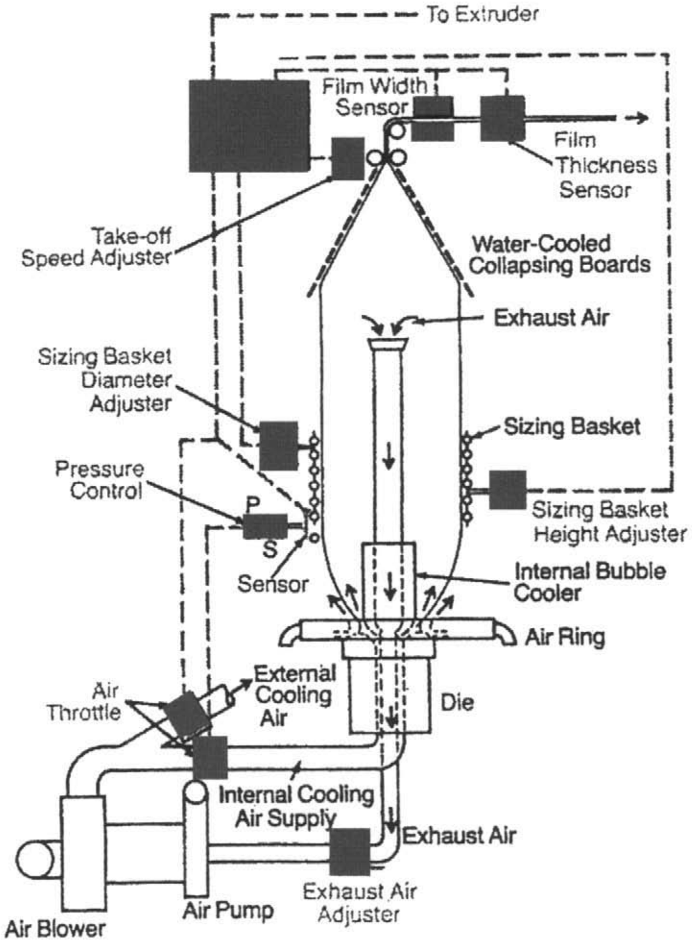

To Extruder
Film Width Sensor
Film Thickness Sensor
Take-off Speed Adjuster
Water-Cooled Collapsing Boards
Exhaust Air
Sizing Basket Diameter Adjuster
Sizing Basket
Pressure Control
P
S
Sensor
Sizing Basket Height Adjuster
Internal Bubble Cooler
Air Ring
Air Throttle
External Cooling Air
Die
Internal Cooling Air Supply
Exhaust Air
Air Blower
Air Pump
Exhaust Air Adjuster

Figure 5.3 Blown film control

Extruder type/performance

The popularly used single-screw and multi-screw types have their differences. Each has its benefits, depending on the plastic being processed and the products to be fabricated. At times their benefits can overlap, so that either type could be used. In this case, the type to be used would depend on cost factors, such as cost to produce a quality product, cost of equipment, life cycle of equipment, and cost of maintenance.

In the past with the development of single-screw extrusion techniques for newer TP materials, it was found that some plastics with or without additives required higher pressures (torque) and needed higher tempera-

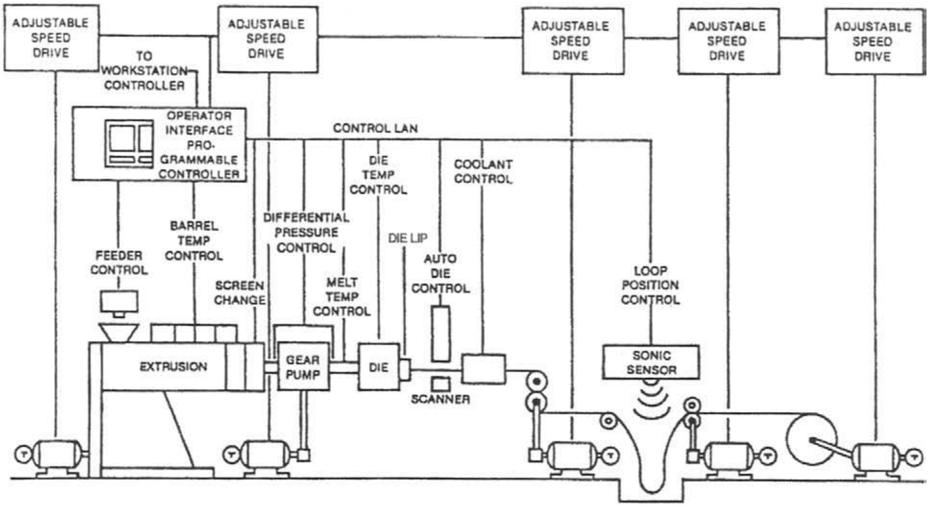

ADJUSTABLE SPEED DRIVE
TO WORKSTATION CONTROLLER
ADJUSTABLE SPEED DRIVE
ADJUSTABLE SPEED DRIVE
ADJUSTABLE SPEED DRIVE
ADJUSTABLE SPEED DRIVE
OPERATOR INTERFACE PROGRAMMABLE CONTROLLER
CONTROL LAN
DIE TEMP CONTROL
COOLANT CONTROL
DIFFERENTIAL PRESSURE CONTROL
DIE LIP
BARREL TEMP CONTROL
FEEDER CONTROL
AUTO DIE CONTROL
LOOP POSITION CONTROL
SCREEN CHANGE
MELT TEMP CONTROL
SONIC SENSOR
EXTRUSION
GEAR PUMP
DIE
SCANNER

Figure 5.4 Sheet line control

tures. There was also the tendency for the plastic to rotate with the screw. The result was degraded plastics. The peculiar consistency of some plastics interfered with the plasticators feeding and pumping process. The problem magnified with bulky materials, also certain types of emulsion PVC and HDPE, as well as loosely chopped PE film or sticky pastes such as PVC plastisols.

In the past twin and other multi-screw extruders were developed to correct the problems that existed with the single-screw extruder. Later the single-screw designs with material developments practically eliminated all their original problems.

The conveyance and flow processes of multi-screw extruders are very different from those in the single-screw extruder. The main characteristic of multi-screw extruders include:

1 their high conveying capacity at low speed;
2 positive and controlled pumping rate over a wide range of temperatures and coefficients of frictions;
3 low frictional (if any) heat generation which permits low heat operation;
4 low contact time in the extruder;
5 relatively low motor-power requirements self-cleaning action with high degree of mixing;
6 very important, positive pumping ability which is independent of the friction of the plastic against the screw and barrel which is not reduced by back flow.

Even though the back flow theoretically does not exist, their flow phenomena are more complicated and therefore far more difficult to treat theoretically than single-screw flow. Result has been that the machine designer has to rely mainly on experience.

Although there are very few twin-screw (TS) extruders in comparison to the many more single-screw extruders, they are used also to produce products such as window and custom profile systems. Their major use is in compounding applications. The popular common twin-screw extruders (in the family of multi-screw extruders) include tapered screws or parallel cylindrical screws with at least one feed port through a hopper, a discharge port to which a die is attached, and process controls such as temperature, pressure, screw rotation (rpm), melt output rate, etc.[143]

Twin-screws with intermeshing counter-rotating screws are principally used for compounding. Different types have been designed that include co-rotating and counter-rotating intermeshing twin screws. The non-intermeshing twin screws are offered only with counter-rotation. There are fully intermeshing and partially intermeshing systems and open- and closed-chamber types. In the past major differences existed between co-rotating or counter-rotating; today they work equally well in about 70% of compounding applications, leaving about 30% where one machine may perform dramatically better than the other.

Similar to the single-screw extruder, the twin-screw extruder, including multi-screw, has advantages and disadvantages. The type of design to be used will depend on performance requirements for a specific material to produce a specific product. With the multi-screws, very exact metered feeding is necessary for certain materials otherwise output performance will vary. With overfeeding, there is a possibility of overloading the drive or bearings of the machine, particularly with counter-rotating screw designs. For mixing and homogenizing plastics, the absence of pressure flow is usually a disadvantage. Disadvantages also include their increased initial cost due to their more complicated construction as well as their higher maintenance cost and potential difficulty in heating.

The market for counter-rotating twin-screw (TS) extruders is basically dominated by two designs. One has cylindrical screws called parallel TS extruder and the other TS extruder is fitted with conical screws. Performancewise, the superiority of the conical principle to parallel does not only appear in the theoretical comparison, but in practice as confirmed by users. Flexibility of conical turns out an extrudate of consistent quality at both low and high output rates which are not sensitive to raw material fluctuations. It appears that the parallel have reached their efficiency limit unless a means of drastically increasing the screw torsional strength is developed. Conical continue to offer what appears to be endless improved benefits through further development.

An example of a conical extruder is Milacron's CM92 that is the world's largest of this design. It produces the highest output extruder for processing wood flour filled plastics. Depending on the flour-plastics ratio, output rate ranges from 1,000 to 1,800 lb/h. It uses a feed crammer to properly handle the low bulk density and fluffy wood flour. The tapered screw design that allows for a larger feed zone and applies a natural compression on the material during processing, results in the wood flour being more effectively "wetted out" by the plastic melt. The large diameter screws [184 tapering to 92mm (7.24 to 3.62in.)] with a 27:1 L/D ratio optimize feed zone surface area for faster, more uniform heat transmission from screws to material. Small exit diameter reduces rotational shear and screw thrust, while increasing pumping efficiency into the die. High torque at low speed of 34 rpm enables gentile plasticizing and a wide processing window.

Critical to this extrusion process is maintaining consistent, controllable heating and cooling. It has five-barrel zones with a total heating capacity of 86 kW. Four of the barrel zones are provided with cooling, using a heat-transfer fluid designed to dissipate heat. Six die zones (including entry adapter) are provided with maximum heating capacity of 45 kW. This extruder was designed with high output capacity in order to provide economic advantages in volume markets such as composite lumber, fencing, decking, windows, and doors.

Operation

Startup

Machine operation can take place in three stages that go from startup to shutdown. The first stage requires operating the extruder for warm-up with operational settings of up-stream and down-stream equipment. The next stage involves setting the required processing conditions to meet product requirements at the lowest cost. The final stage is devoted to fine-tuning and problem solving the complete line. A successful operation requires close attention to many details, such as the melt quality, temperature profile adequate to melt but which does not degrade the plastic, production of a minimum of scrap, and procedures for startup and shutdown that will not degrade (or minimize) the plastic. Processors must also become familiar with troubleshooting guides.[143]

Extrusion operation differs based on the type of product to be produced and plastic to be processed. However on startups there are some aspects which all processes have in common. The process differs somewhat if one has a clean, empty machine, or one which contains plastic and is reheated. A main source of difficulty in starting an extrusion run is impatience of people. It is necessary to wait until the barrel and die is at the correct operating temperature before starting otherwise problems develop such as having hot or cool melt spots, overstressed melt sections, overloading the screw with plastics, plastic bridging at the hopper, degrading plastic, etc. Starve feeding of plastic on startup at a low screw speed and until melt is pumped from the die helps prevent bridging of the screw.

Consider purging the extruder plasticator when it contains plastic that can be detrimental to startup and/or producing unacceptable products (Chapter 3). If a plastic was left in the barrel for a while, with heat off, the processor must determine if the material is subject to shrink. It could have caused moisture entrapment from the surrounding area, producing contamination that would require cleanup (this situation could also be a source of corrosion in/on the barrel/screw). Even with the same plastic in the machine from a previous run, the entire machine should be cleaned and/or purged, including the hopper, barrel, breaker plate, die, and downstream equipment.

When starting up a new extrusion setup, start the screw rotation at about 5 rpm. Gradually look into the air gap between the feed throat and throat housing and make sure the screw is turning. Screws have been installed without having their key in place, or the key has fallen out during installation. Also make sure that antiseize material is applied to the drive hub, to help installation and removal. Also if the key is left out and the drive quill is turning and the screw is not, the screw will not gall to the drive quill.

Prior to startup one must check certain machine conditions and process control that should be listed on some kind of worksheet from the machine manufacturer, plastic supplier, and/or the more important plant setup person with experience (Chapter 3). Checkup includes the careful handling of:

(a) heater bands and electrical connections,

(b) thermocouples, pressure transducers, and their connections,

(c) inspect all machine heating, cooling, and ventilation systems to ensure adequate flow,

(d) be sure flow path through the extruder is not blocked,

(e) have a bucket or drum, half filled with water, to catch extrudate wherever purging or initial processing of plastics were contaminated gaseous by-products exist,

(f) review operating manual of the machine for other startup checks and requirements that have to be met such as motor load (amperage) readings.

Within various types of the family of plastics (PE, PVC, PP, etc.) each type usually have different heat profiles and other settings (Table 5.1). Experience shows how to set the profile and/or obtain preliminary information from the material supplier. Degrading or oxidizing certain plastics is a potential hazard that occurs particularly when the extruder is subject to frequent shutdowns. In this respect, the shutdown period is even more critical than the startup period.

In setting up the barrel temperature profile start with the front to rear zones (die end to feed section). The heat controllers are set slightly above the plastic melting point prior to turning on the heaters. Heat-up should be gradual from the ends to the center of the barrel to prevent pressure buildup from possible melt degradation. With this startup follow through with:

1 gradually increase heaters, checking for deviations that might indicate burned-out or run-away heaters by slightly raising and lowering the controller set point to check if power goes on and off,

2 following with all heaters slightly above the melt point, adjust to the desired operating heats; time required to reach temperature equilibrium may be ½ to 2 h, depending on the size of the extruder,

3 if overshooting occurs it is usually observed with the on/off controllers,

4 after set heats have been reached, one puts the plastic in the hopper and starts the screw at a low speed such as 2 to 5 rpm; some plastics, such as nylon, may require 10 to 20 rpm.

5 processor should observe the amperage required to turn the screw, stop the screw if the amperage is too high, and wait a few minutes before restart,

6 observe and remain at the required melt pressure, the extruder barrel pressure should not exceed 1,000 psi (7 MPa) during the startup period,

7 machine should run a few minutes and purge the initial run until a good quality extrudate is obtained visually; experience shows what it should look like such as a certain size and amount of bubbles or

fumes may be optimum for a particular melt, based on one's experience (or the trainer's experience) after setting up all controls,

8 turn up the screw to the required rpm if not already properly set, checking to see that maximum pressure and amperage are not exceeded,

9 when time permits, after running for a while, the processor should consider stopping the machine, let it start cooling, and remove the screw to evaluate how the plastic performed from the start of feeding to the end of metering. Thus one can see if the melt is progressive and can relate it to screw and product performances.

10 adjust the die with the controls it contains, if required, at the desired running speed

Once the extruder is running at maximum performance, set up controls for takeoff/downstream equipment, which may require more precision settings and/or changes in the extruder to meet downstream equipment requirements.

Extrudate can start its tract from the die by threading (or the term also used is stringing up) through the cooling and take-off downstream equipment to its haul-off initially at a slower speed than production operation. When possiblem rather than taking the extrudate from the die and being directed through the equipment, the hot melt is made to weld to the thread-up end already in the equipment that is usually a left over from the previous run. In turn the thread-up is pulled through the line carefully and safely. If a welding action does not occur, a metal hook may be pushed into the melt. Cooling of this joint is required to give it strength. Care is needed to avoid making a lump too large to go through the line.

This operation requires the personal skill of the startup person. That person is required to integrate/interrelate extruder and down-stream equipment. Extruder screw speeds and haul-off rates may then be increased. Downstream equipment is adjusted to meet their maximum operating performance, such as having the vacuum tank water operate with its proper level and vacuum applied. The extruder can be fine-tuned to obtain the final required setting for meeting the desired output rate and product size.

Startup operations are made at rates people can handle. The process is very slow compared to standard operating speeds. The puller starts its movement at just about the same speed the person has been pulling or there may be a pile-up or tear-off of melt at the die. That will usually mean threading up again.

Skill on the part of the person will involve pulling continuously at a steady rate. The person acts like a machine or robot for a few minutes. Skill on the part of a good operator is very evident at startup.

Cooling the extrudate during hand pulling is important. It gives strength and form stability to the extrudate. Without cooling, the melt will string out and pull apart. The steadiness of pulling and the evenness of cooling determine what the hand-pulled product will look like and how easily it can be threaded and fed into the take-off.

After this operation follow up on the product's dimensions or what would determine that the product is meeting requirements. Minor changes in speed may be needed. Adjustments to centering of the die or die opening may be necessary if there are thick or thin spots. Product measurement and die adjustment is continued until a satisfactory product is made. Frequently this process may take an hour or more. During this time, scrap is produced and when practical should be used as a regrind and reused. To reduce this time schedule significantly program controllers provide a quick means to balance out all the control settings to produce the desired product.

Shutdown

It is common to run the extruder to an empty condition when one is shutting down. This action ensures that there is no startup with cold plastic, a condition that could overload the extruder if improper startup occurred. Some extruders, such as those processing PE film, are shutdown with the screw full of plastic. This prevents air from entering and oxidizing the plastic. Because PVC decomposes with heat, to ensure that this material is completely removed at shutdown, purging material such as low melt PE is processed that can remain in the barrel (Chapter 3). On startup, it is preferable to raise barrel heat slightly above its normal operating temperatures. The higher temperature ensures that unmelted plastic will not produce excessive torque in the screw. In regard to the downstream equipment, such as with film or sheet lines, consider leaving some "threading" for an easy startup as reviewed in startup.

The shutdown is usually very simple. Procedures for shutdown without cleanout starts by stop feeding plastic into the plasticator and reduce all heat settings to the melt heat. Reduce the screw speed to 2 to 5 rpm, purging the plastic if requires into a water bucket or drum prior to reducing the melt heat. The screw rotation continues until no more plastic exits the die. Rotations of the screw stops resulting in the so-called pumping the screw dry of plastics.

With the screw stopped, shut off the heaters and disconnect the crosshead (or die) heaters. Reduce other heaters to about 170 to 330C (400 to 625F) depending on the plastic's temperature at the melt point.

If a screen pack with breaker plate is used, disconnect the crosshead (or die) from the extruder and remove the breaker plate and screen. If necessary, appropriate action is taken to clean them (Chapter 17).

For clean out of the extruder at shutdown, disassemble the crosshead and clean it while still hot. Remove the die, and gear pump if used, and remove as much plastic as possible by scraping with a copper spatula or brushing with a copper wire brush. Remove all heaters, thermocouples, pressure transducers, and so on. Consider using an exhaust duct system above the disassembly and cleaning area, even if the plastic is not a contaminating type. This procedure keeps the area clean and safe.

Follow by pushing the screw out gradually while cleaning with a copper wire brush and copper wool.[93] Care should be exercised if a torch is used to burn and remove plastic; tempered steel may be altered and the screw distorted or weakened as well as subjected to excessive wear, corrosion, or even failure (broken).

After screw removal, continue the cleaning, if necessary. Follow by turning off the main electric power switch. Final cleaning of products, particularly disassembled parts, is best done manually, or much better, in ventilated burnout ovens, if available, operating at about 1,000F (540C) for about 90 min. For certain parts with certain plastics, the useful life could be shortened by corrosion; check with the part manufacture. After burnout, remove any grit that is present with a soft, clean cloth. If water is used, air-blast to dry. With precision machined parts, water cleaning could be damaging because of the potential of corrosion when certain metals are used.

Film and sheet

Films and sheets are produced in several ways, including extrusion, calendering, and casting. Method used involves the properties required of the basic plastics and finished products as well as cost usually based on quantity. The following classification can be helpful as a guide to film and sheet thicknesses: (1) film is generally less than 0.010 in. (0.003 mm) and (2) sheet at 0.010 in. or more. In turn sheet can be classified as:

(a) intermediate sheet in the range of 0.040 to 0.250 in. (0.01 to 0.06 mm);

(b) thin gauge sheet up to 0.060 in. (0.015 mm);

(c) heavy gauge sheet at 0.080 to 0.500 in. (0.02 to 0.13 mm).

Most commercial plastic films are produced with a thickness of less than 0.005 in. and most packaging films are less than 0.003 in. Different groups within the different industries (plastic, packaging, aluminum, clothing, etc.) may have their own thickness definitions; they call it what their buyer/customer use. Some of them use 0.004 in (0.10 mm) as the dividing line between film and sheet.[199]

Film

Film can be produced either by extrusion tubular blowing or flat process. Each has its advantages and disadvantages. These processes result in film with a molecular orientation predominantly in the machine direction (MD). As reviewed later, orienting the film can be in two orthogonal directions that develop superior optical, mechanical, and physical properties. The process is known as biaxial orientation and it can be applied to both tubular and flat film.

Regardless of process, film production lines include common downstream equipment such as haul-off, tensioning, and reeling stations. Other common features include static control units and corona discharge treaters to prepare the film surface for subsequent printing processes. A high purity melt, free of inclusions, is essential for film production. This is achieved by filtering the melt through a screen pack upstream of the die.

Blown Film

Figure 5.5 provides an example of a complete operating line that produces film. Table 5.3 provides an introduction to production output yields.

The blown film process involves extruding a relatively thick tube that is then expanded or blown by the usual internal air pressure or the water quench process to produce a relatively thin film (Figure 5.6). The tube can be collapsed to form double-layer layflat film or can be slit to make one or two single-layer film webs. The water quench process is the generally preferred method of producing blown PP type film.

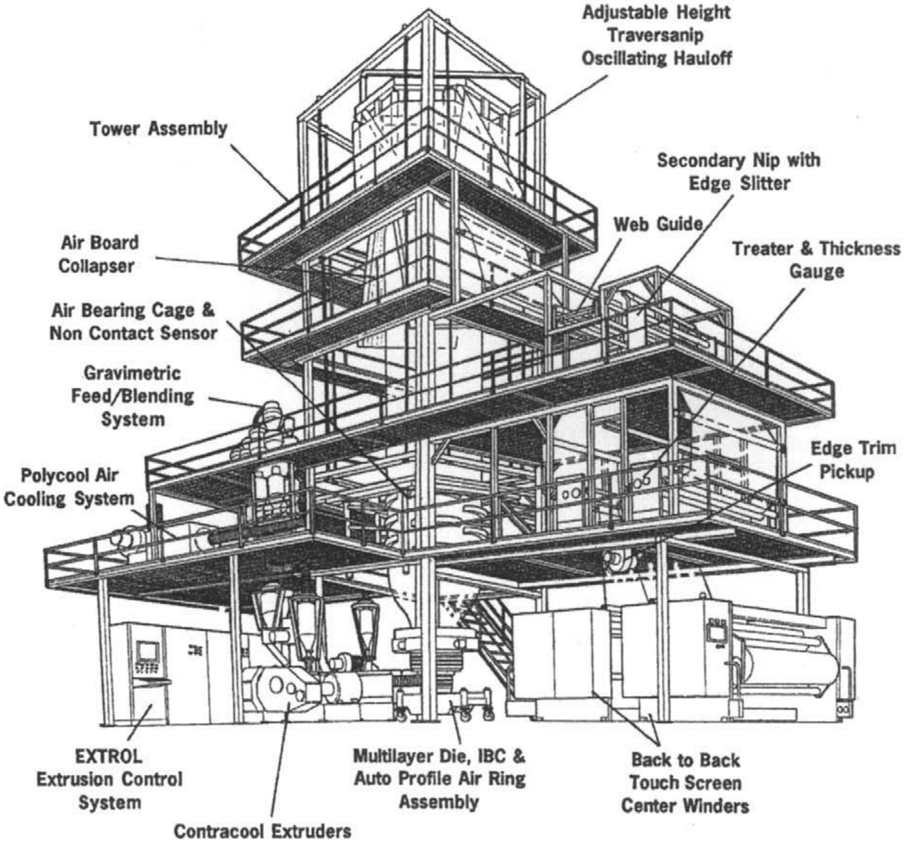

Adjustable Height
Traversanip
Oscillating Hauloff
Tower Assembly
Secondary Nip with
Edge Slitter
Web Guide
Treater & Thickness
Gauge
Air Board
Collapser
Air Bearing Cage &
Non Contact Sensor
Gravimetric
Feed/Blending
System
Edge Trim
Pickup
Polycool Air
Cooling System
EXTROL
Extrusion Control
System
Multilayer Die, IBC &
Auto Profile Air Ring
Assembly
Back to Back
Touch Screen
Center Winders
Contracool Extruders

Figure 5.5 Assembled blown film line (courtesy of Battenfelt Gloucester)

Blown film is usually extruded vertically upward through a circular die. This forms a tube that is then blown into a bubble that thins or draws down to the required final gauge. Orientation takes place in two directions horizontally (transverse direction/TV) as the bubble is formed, and in the machine direction (MD) as controlled by adjustable-speed haul-off nip rolls.

Air ring either with single lips, or two or more lips direct air to cool the bubble at the die exit. Internal bubble cooling is used to cool the inner surface of the extruded bubble to gain high production rates (typically 50% higher than with external air only). The bubble enters a collapsing frame and, after passing through upper nip rolls, becomes a tube that can then be processed into bags, flat film by slitting open the tube, etc. Because convection cooling is relatively slow, blown film tends to be hazier than flat cast film.

Table 5.3 Examples of film yields

	Yield			
Material	*(yd^2/lb) 0.001 in thickness*	*(m^2/kg) 0.025 mm thickness*	*(lb/1000 yd^2) 0.001 in thickness*	*(g/m^2) 0.025 mm thickness*
Cellulose acetate	17	31	59	32
Cellulose tri-acetate	16	30	62	33
Nylon	18.5	34	54	29
Polyethylene				
low density	23	43	43	23
high density	22	41	45	24
Polyethylene terephthalate	15.5	28	65	36
Polypropylene	24	44	42	23
Polystyrene	20	37	50	27
Polyvinylidene chloride	17	31	59	32
PTCFE	10	18	99	55
PTFE	10	18	99	55
PVC				
flexible	14.5–17	27–31	59–68	32–37
rigid	15.5	28	65	36

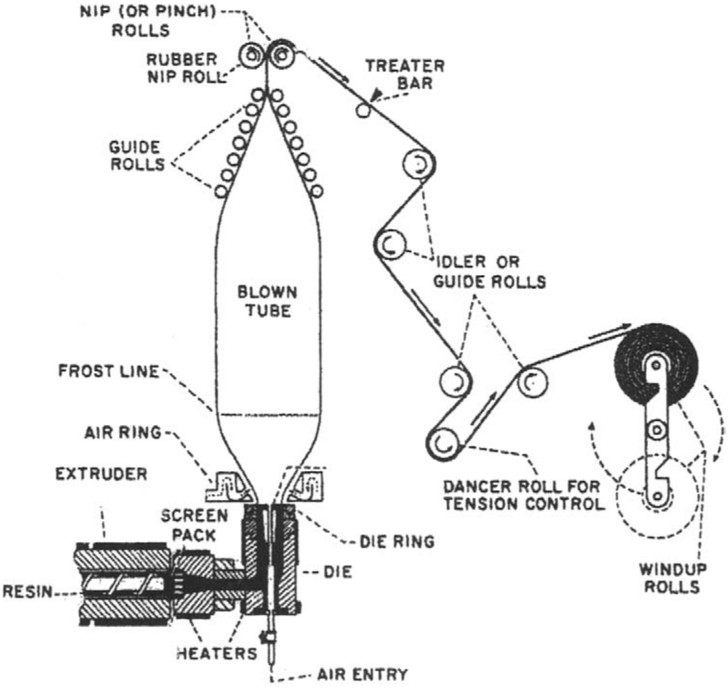

NIP (OR PINCH) ROLLS
RUBBER NIP ROLL
TREATER BAR
GUIDE ROLLS
IDLER OR GUIDE ROLLS
BLOWN TUBE
FROST LINE
AIR RING
EXTRUDER
SCREEN PACK
DANCER ROLL FOR TENSION CONTROL
DIE RING
DIE
WINDUP ROLLS
RESIN
HEATERS
AIR ENTRY

Figure 5.6 Blown film line schematic with more details

The rotating speed of the nip rolls is a major source for controlling the rate that the bubble is drawn. At the end of the line, winder technology allows the selection of surface winding, center winding, and a combination of surface/center winding to suit the film behavior being run. They may be wound directly as a lay flat tube, slit at both sides and wound into two flat reels, very wide film slit on one side (so that they can be opened with a visible line due to the fold), and other constructions such as an in-line grocery bag line.

Trapped air that forms the continuous tube is directed through a mandrel via the die. Once the bubble has been formed, the controlled air pressure required to keep the bubble stable is kept constant. Usual pressure is about 40 ft^3/min (1.1 m^3/min).

The bubble diameter is normally always much greater than the die diameter. This bubble diameter divided by the die orifice diameter is called the blow-up ratio (BUR). The BUR is usually 1.5 to 4.0, depending on the plastic being processed and the thickness required. The bubble diameter must not be confused with the width of the flattened double layer of film between the nip rolls. The width of this double layer is 1.57 times the bubble diameter and is called the blown-film width (BFW).

With crystalline types [not amorphous (Chapter 1)], melt leaving the die (and moving to a ring-shaped zone where the film approaches its diameter) changes from a hazy to a transparent (amorphous) condition. The level at which this transition occurs is the frost line. This zone is characterized by a "frosty" appearance to the film caused by the film temperature falling below the softening range of the plastic.

Gauge thickness can be extremely non-uniform due to melt behavior on exiting the die and/or distortions of the collapsing frame. To provide uniformity controlling the melt is required. Different techniques are used to handle the film such as oscillating or rotating dies and oscillating film hauloffs. The different systems available meet different requirements such as web width, cooling system effect, degree of tackiness, stiff film, line speed, and/or gauge thickness.[143] There are computer Hosokawa Alpine systems capable of automatic startup; push a few buttons and the line is set-up in 4½ minutes.[476]

Flat Film

Flat film identifies cast film. Other names used include chill roll film, roll cast film, slot cast film, water quench, water chill film, etc. These cast film lines require dies that yield a wide range of diverse products. Widths may range from less than 6 in. (15 cm) to more than 33 ft

(10 m) for geomembranes. The function of a flat die is to distribute the molten plastic pumped into the die's center by the extruder to the desired end-product width, develop a uniform flow pattern, and establish the desired product thickness. Successful operation begins with a good flow channel design. The flow channel of the die is the most intricate part of the die to machine because the geometry is complex, the tolerances are critical, and the highly polished surface finish requirements are stringent (Chapter 17).

Cast film is produced by extruding the melt from a slit die and cooling it either by contact with a chill roll or by quenching in a water bath. The most popular process used to produce the flat film is with the chill rolls. Chill roll lines can be arranged in different layouts to meet different requirements. Example is shown in Figure 5.7. Water chill tank or quench film is also a popular process.

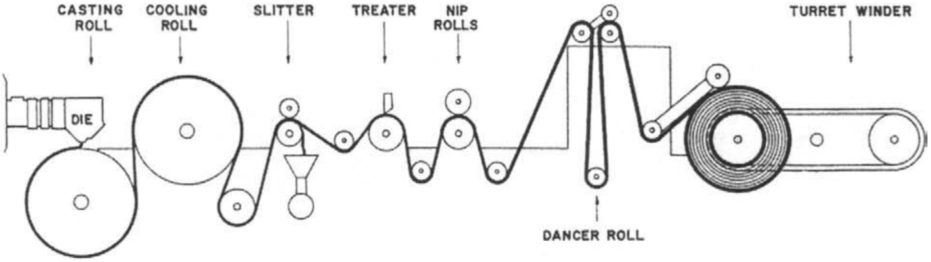


Figure 5.7 Schematic of flat film chilled roll-processing line

Since this contact-type cooling is faster and more uniform than air-cooled systems used for blown film, higher production rates are met with cast film. Cast film tends also to be clearer and with less thickness variation than blown film. Film produced on the cast process is used in high-speed converting operations such as laminating and multicolor printing, as well as in packaging applications where high clarity and gloss are desirable.

A method of pinning/locating the film on the chill roll is normally required to realize high line speeds. This is achieved by the use of an air knife to force the molten web in contact with the casting drum. Also used is a vacuum box that removes the layer of air from the surface of the chill roll and draws the molten web to the casting roll by vacuum. The edges of the cast film also have to be pinned to the casting roll to achieve high production rates. Air jet edge pinners or electrostatic pinners do this.

The die is maintained in close proximity (typically 40 mm to 80 mm) to the chill roll so that the low-strength melt web remains unsupported for a minimal distance and time. If the die is too close, there is insufficient space for thickness draw-down and widthwise neck-in (Figure 5.8 where m = width at die, f = width on chill roll, m – f = total neck-in) to take place in a stable manner. With neck-in a beading occurs on both edges of the film. Down the extrusion line these beads are later trimmed away.[200]

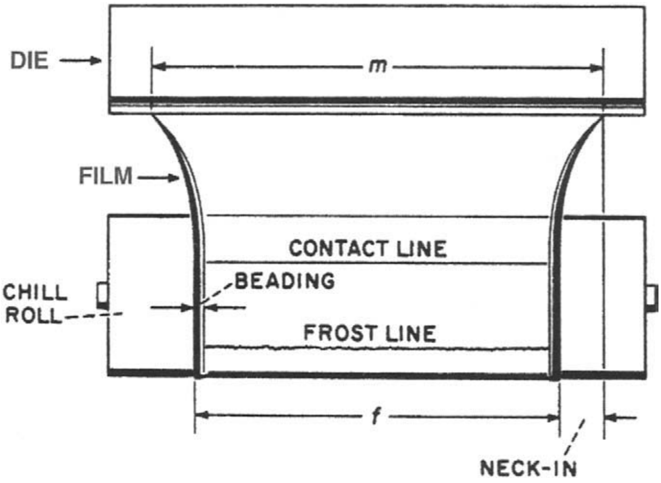


Figure 5.8 Example neck-in and beading that occurs between die orifice and chill roll

The water quench cast film process (Figure 5.9) is similar in concept to the chill roll process and uses similar downstream equipment. A water bath takes the place of the chill rolls for film cooling, and by cooling both sides of the film equally, it produces a film with slightly different properties compared to chill roll cast film. Its slit die is arranged vertically and extrudes a melt web directly into the water bath at close range. The bath is typically maintained at 20C. The film passes under a pair of idler rollers in the bath and, for any given rate of extrusion, it is the rate of downstream haul-off that regulates film draw-down and finished thickness.

Sheet

The thickness range of extruded sheet is normally between 0.010 and 3 in. Generally, 0.500 in. is the upper limit in the conventional range,

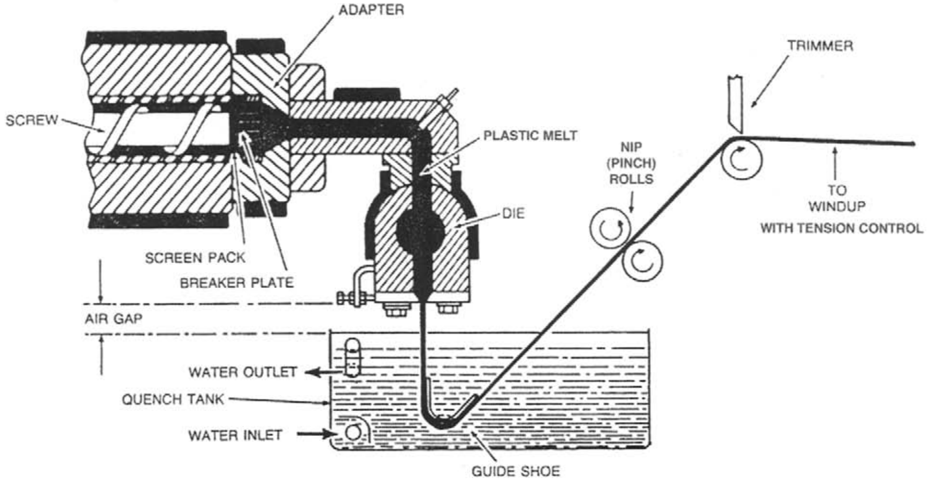

ADAPTER
TRIMMER
SCREW
PLASTIC MELT
NIP (PINCH) ROLLS
DIE
TO WINDUP WITH TENSION CONTROL
SCREEN PACK
BREAKER PLATE
AIR GAP
WATER OUTLET
QUENCH TANK
WATER INLET
GUIDE SHOE

Figure 5.9 Simplified water quenched film line

with higher thicknesses associated with specialty products and process techniques. Widths can be up to at least 10 ft (3 m). The sheet material can be thermoformed (estimated that 60% of sheets are thermoformed), or fabricated by blanking, punching, machining, and welding (Chapter 7). Key characteristics of sheet include a good ratio of strength and rigidity to thickness, toughness, resistance to moisture, resistance to sterilization procedures, good moisture barrier properties, chemical resistance, and/or non-toxicity.

The most popular method to produce sheets is using an extruder with polished stacked rolls that could include the use of an air knife (Figures 5.10 and 5.11). There is the extrusion process where an annular pipe-like cross section die is used (Chapter 17). The extrudate is slit in one or more places and then flattened via rolls into a sheet. In addition to using

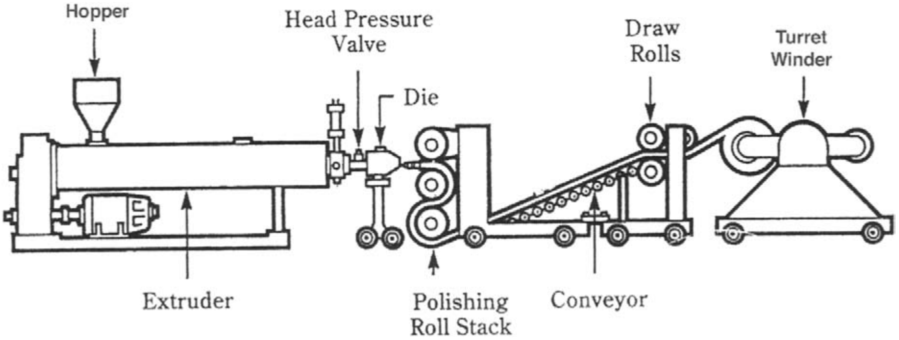

Hopper
Head Pressure Valve
Die
Draw Rolls
Turret Winder
Extruder
Polishing Roll Stack
Conveyor

Figure 5.10 Schematic of sheet line processing plastic

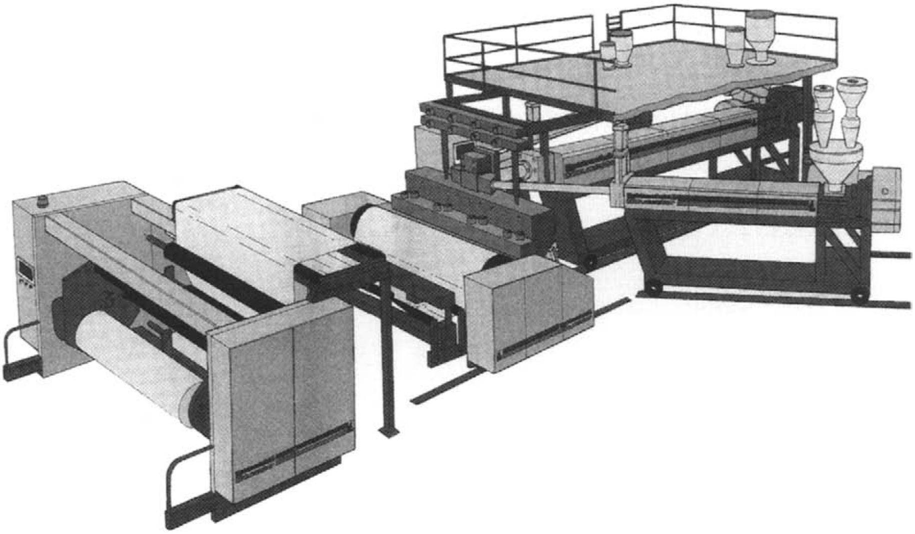


Figure 5.11 Coextruded (two-layer) sheet line

extruders this system is one of the methods used in foam sheet production. With large production orders use is made of calenders (Chapter 9).

From the die, the sheet passes immediately to a cooling and finishing device in the form of a roll-cooling stack. The usual configuration is a three-roll vertical stack with the sheet entering at the nip between the upper two rolls (Figure 5.12). To meet certain processing requirements variants include up-stack working where the sheet enters between the lower two rolls, a horizontal roll stack used with a vertical die for low viscosity melts, a two-roll stack for thinner sheet gauges, and others to meet different material requirements. The function of a stack is to cool and polish the sheet. Alternatively, an embossed roll may be used to impart a texture to the sheet surface.

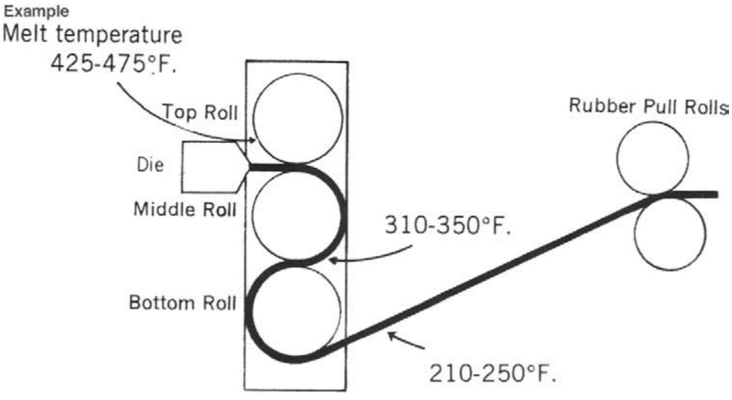

Example
Melt temperature
425-475°F.
Top Roll
Die
Middle Roll
Bottom Roll
Rubber Pull Rolls
310-350°F.
210-250°F.

Figure 5.12 Schematic of a three-roll sheet cooling stack

Stack rolls are usually of double shell design, giving internal high velocity liquid circulation at a controlled and uniform temperature. Each roll is equipped with its own individual temperature control system which is built into the take-off unit. The sheet gradually continues to cool as it travels around the rolls becoming sufficiently solidified so that it can continue down the line.

Different combinations of extruded sheets (films, etc.) are laminated usually by pressure bonding or adhesive bonding. These lay-ups provide different commercial products. When possible and practical, such as having sufficient quantity, it is usually more economical to coextruded. Laminated sheet products also can be made using the extruder three roll stacks when extruding plastic. Laminating or capping a roll of sheet, film, tape, or any web material can be accomplished by unwinding a roll supported above the stack.

Extruded polystyrene foam (major plastic used) sheet can be produced on systems utilizing specially designed single- or tandem-screw extruders (Figures 8.1). Most production is done with tandem (two) single-screw equipment consisting of a primary extruder with blowing agent injection system delivering melt to the second cooling extruder, with annular die, sizing mandrel followed with pull roll unit, and one or more winders (Chapter 8).

Pipe and tube

Pipes and tubes are extruded in a wide range of sizes, from medical small tubes and drinking straws up to pipes of many feet in diameter. Plastic pipes and tubings have different definitions that are usually associated with the different industries (plumbing, gas transmission line, beverage, medical, mining, and so on). A popular definition for pipe is that they are rigid, hollow, long, and larger in diameter than tubes. Tubings are basically the same except flexible and smaller in diameter such as up to 0.5 in. (0.13 mm). Practically all pipes are extruded using TPs. Single screw extruders are usually used but with PVC twin screw extruders are also used. Dies in some of the line use the same basic type dies and plastic melt temperature ranges used in wire coating (Chapter 17).

The extruder and die, as well as down-stream devices for the outside and inside calibration of the pipes cross sectional area, if required, use air pressure and/or vacuum to contain the pipe shape. Wall thickness measuring device, mandrel designs (such as while water cools outside;

inside a thin spiral gap between the fixed mandrel attached to the die provides cooling air), cooling tank, and automatic cutting with pallet equipment for rigid pipe or windup unit for flexible pipe are downstream. The line could include a marking device, testing device, etc. An important requirement is to cool the extrudate rather fast near the die while keeping control of dimensions and properties.

Included in the processes are various techniques to control the dimensions/sizes that are either free drawn melts (usually for the small diameter tubes) or sizing fixtures. Dimensional and/or thickness calibrating disks of different designs are used. There are small diameter tube lines using draw down control (free extrusion) sizing technology where the extruded tubular melt has no calibrating device after leaving the die. It could have internal air pressure so that the tube does not collapse upon leaving the die. Devices are also used with different designed calibrating/sizing plates or tubes with or without pressure or vacuum assist in and/or outside the tube (Figure 5.13).

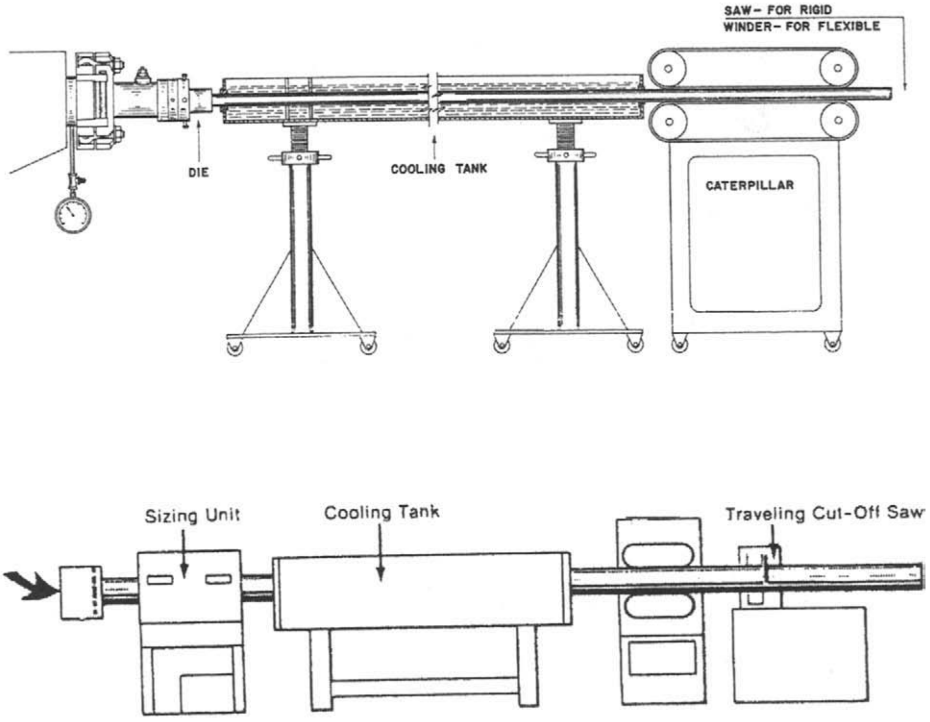


Figure 5.13 Introduction to downstream pipe/tube line equipment

Dies for pipe production consist essentially of a female die ring that shapes the pipe outside diameter, and a male mandrel that shapes the inside diameter. The difficulty is to support the mandrel in rigid and accurate alignment with the die ring without compromising the product. The spider type uses three or four spider legs to support the mandrel but these legs cause axial weld lines as the melt flows around them (Chapter 17).

Profile

There are many different shaped profiles. These profiles identify many varieties of shapes. Pipes and tubes could be included but the industry has had them classified as a separate category because they represent major and large markets on their own. Profiles normally identify shapes that are noncircular or are not symmetrical. However, there are exceptions where extruded products, such as capillary tubing and rod, are usually called profiles. They can be solid, hollow, or a combination of solid and hollow. Popular shapes include many hollow sections such as in window frame profiles, tapes, edgings, and gaskets as well as a combination of rods with different cross sections; structural shapes in the form of Ts, Us, Is, Hs, squares, etc. The product shapes and sizes are as limitless as the number of applications.

Profile fabricating processes are a takeoff of the methods used in processing pipes, tubes, and other products. Most profiles are extruded horizontally through dies similar to the product cross sections. The extrudates are cooled and sized with air jets, water troughs, cooling sleeves, mechanical aids, specially designed frames, dimensional measuring devices, and/or their combinations. Flexible to rigid shapes is produced which in turn at the end of the line are coiled or cut to required lengths.

Industry requirements for profiles range from very loose to very tight tolerances. Extruder specifications for a tight process capability include three critical areas of consideration. First the temperature control on the barrel is paramount for a stable process. Many PLCs (programmable logic controllers) exceed requirements; however, PID (proportional-integral-differential) instrumentation will also hold a ±1F on barrel control (Chapter 3). Secondly, a tight drive control screw coupled with a motor capable of holding 0.01% speed control with one percent drift are used. Thirdly, the screw design should be specific to the TPs being extruded (Chapter 3).

The big profile market is in many small-specialized plants. This end of the business represents a large market that requires short runs. Usually the profiles are small dimensionally and only require small extruders. Most of these plants design their dies and have their own machine shop to make rather inexpensive plate dies. They may also do their own plastic compounding since many runs are limited materialwise but exchanges in profile shapes may be extensive. To setup these lines for small operations generally requires personnel with experience and skill.

There are large production runs that are made by rather large profile fabricating plants. These plants operate like the major extrusion plants extruding film, sheet, pipe, etc. They can produce long runs providing low costs for products such as building sidings, building tongue and groove panels, strappings, etc. Building and other profiles are used with and without fillers (cement, plastic foams, etc.) to provide different aesthetics and/or structural benefits.

An extruder die's orifice is usually made oversize to the shape and size of the required contour. The final shape develops downstream from the die as the plastic expands, warps and/or shrinks. The best designs are based on past experience with a particular profile shape. As usual experience or being trained by one with experience has always been a real plus.

For simple shapes such as solid and "V" profiles with no close tolerance requirements, a free extrusion technique can be used. The plastics processed are those with high viscosity and softer grades, particularly when extruding at the lowest possible melt temperature. They can be used for short runs and prototyping with inexpensive dies that can, in many cases, be made from single or multiple flat plates [Figure 5.14(a)]. This type die could be a single or multiple array of thin plates with the orifice machined; the orifice opening could include tapers, etc. Designing and manufacturing precision dies to produce tight tolerance controlled profiles are shown in Figure 5.14(b) (Chapter 17).

For long runs the plate dies have the disadvantage of encouraging a buildup of stagnant plastic on the rear of the plate and eventually degrade the plastic producing unacceptable profiles. Usually no melt-degrading problem develops before the short run is completed. Or if the problem starts developing, the plate die is dismantled and cleaned.

As the fluid plastic melt leaves the die, it usually has to be supported by a shaping fixture or sizing fixture. It retains a desired shape through the period when the plastic cools. A metal cooling device (steel or brass sleeve, flat sizing plates, etc.) can be used. Cooling is provided by a water trough/tank and/or a water cascade, except for those rigid plastics that can be cooled in air. With certain plastics, water-cooling sets up internal stresses and gives a poor surface appearance. Other

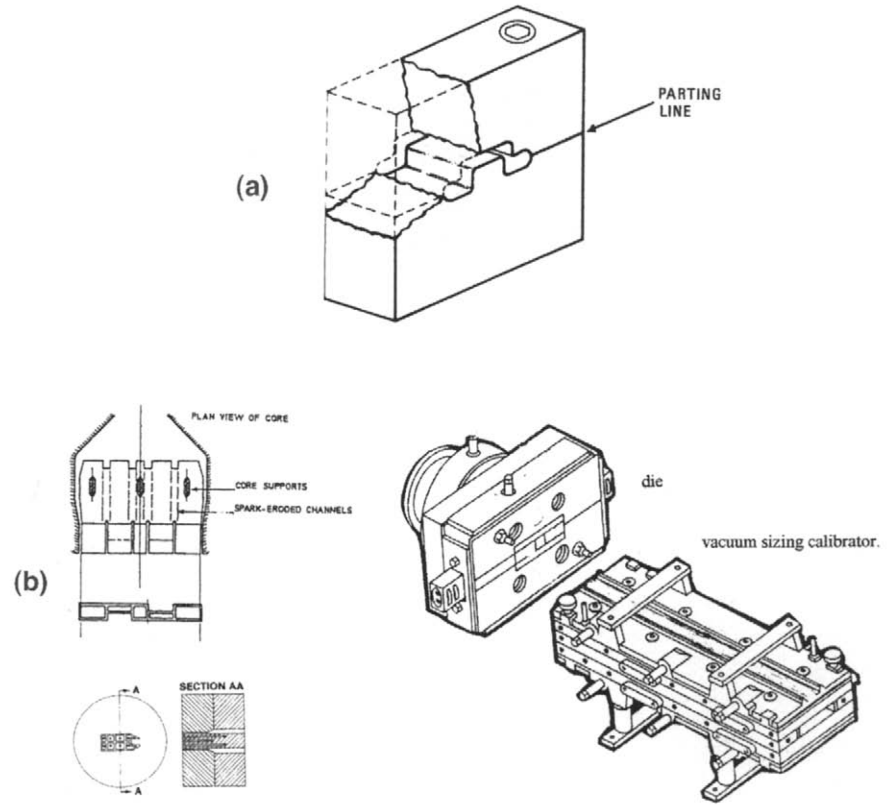


Figure 5.14 (a) Example of an inexpensive plate die.
(b) Examples of precision dies to produce close tolerance profiles

techniques are used to speed up the line such as cryogenic or nitrogen liquid cooling.

Extruding thick/large rods can set up problems. They require special care in order to eliminate voids. Some plastic rods, particularly small diameters, have no problems. Different techniques are used. One well-established approach is to ensure that the plastic melt is packed and moves at a sufficiently low output rate so the relationship of pressure, time, and output rate is closely controlled. A die with a sizing tube is attached to the die face. This sizing tube is also called a cooling die or forming die. A jacket that continually has water flowing through and around the jacket surrounds the sizing tube. It could include baffles and restrictions to direct the water's entrances and exits in different sections so that a temperature profile cascading flow exists.

Plastic melt is pumped into and through this sizing tube. The melt starts to freeze/solidify as soon as it touches the inner cool wall of the sizing tube. A hardened skin forms and slides along the metal wall surface. While it moves, the skin becomes thicker. In the meantime, the plastic shrinks; however the cooling action has not reached the rod's core. With the proper rate of flow, the extruder pumps more plastic melt to pack the interior with more plastic.

The packing action eliminates the voids. The plastic continues to go downstream while it starts with surface cooling and the internal packing. To ensure cooling action from the sizing tube internal wall to the plastic's wall surface (avoiding shrinking away from the jacket wall), the jacket inside wall diameter is reduced down-stream to permit contact of the plastic. This action is usually not required if the packing action causes the plastics to continually press and slide along the straight-bored jacket hole. Before the rod leaves the sizing tube, it is sufficiently cooled along the complete cross section. This packing action is similar to what happens when filling a mold during injection molding.

Rod extrusion is a slow process because the plastic is a poor conductor of heat. Output rate may be about 9 to 23 kg/h (20 to 50 lb/h). After extrusion, these rods are usually annealed for stress relief and stabilization of dimensions. If required by design, they can be centerless ground to final size.

Different extrusion profile processes can be used such as a robotic profile. A robot delivers the hot melt over or around a substrate. This robotic extrusion process can uses a flexible, heated, high-pressure hose that is connected to the extruder's die exit. The hot melt travels through the hose. At the end of the hose is a nozzle; the tip of this nozzle is, in effect the actual profile die. A computer-regulated multi-axis robot controls the positioning of the profile nozzle die. The nozzle/die is guided by the robot to deposit the profile's hot melt on, as an example, a substrate that is on a multi-station rotating table supporting other substrates to be covered.

Coating

Many different processes are used to coat or laminate; there are literally hundreds of different processes used just to coat materials (Table 5.4) (Chapter 10). An important coating method involves the extruder, particularly for long runs. The extruded dedicated fast lines are used since they provide quality controlled products and are very cost effective.

Table 5.4 Guide or different information pertaining to different coating methods

Coating method	*Base material*[a]	*Coating composition*[b]	*Usual coating speed ($m\,min^{-1}$)*	*Viscosity range, (mPa s)*	*Wet-coating thickness range (μm)*
Air knife	B, D	P, T, X	15–600	1–500	25–60
Brush	B, C, E, F, G	R, S, X, Z	30–120	100–2000	50–200
Calender	A, B, D, E	U, V, W	5–90		100–500
Cast-coating	A, B, D	Q, R, S, T, V, Y	3–60	1000–5000	50–500
Curtain	A, B, C, D, E, F	R, S, V, X, Z	20–400	100–20 000	25–250
Dip	A, B, D, E, F, G	R, S, V, X, Y, Z	15–200	100–1000	25–250
Extrusion	A, B, D, E	T, U, V, W	20–900	30 000–50 000	12–50
Blade	A, B	R, S, T, V, X, Y, Z	300–600	5000–10 000	12–25
Floating knife	A, B, D	R, S, T, V, X, Y, Z	3–30	500–5000	50–250
Gravure	A, B, D, E	R, S, T, U, V, Y, Z	2–450	100–1000	12–50
Kiss roll	A, B, C, D, E, F	R, S, V, X, Z	30–300	100–2000	25–125
Knife-over-blanket	A, B, D	R, S, T, V, X, Y, Z	3–30	500–5000	50–250
Knife-over-roll	A, B, C, D, E	R, S, T, U, V, X, Y, Z	3–60	1000–10 000	50–500
Offset gravure	B, D	R, S, T, Z	30–600	50–500	12–25
Reverse roll	A, B, C, D, E, F	R, S, T, U, V, X, Y, Z	30–300	50–20 000	50–500
Reverse-smoothing roll	A, B	R, T, X	15–300	1000–5000	25–75
Rod	B, D	R, S, T, V, X, Y, Z	3–150	50–500	25–125
Sprays					
Airless spray	A, B, C, D, E, F, G	S, T, V, X, Y, Z	3–90	c	2–250
Air spray	A, B, C, D, E, F, G	S, T, V, X, Y, Z	3–90	c	2–250
Electrostatic	A, B, C, D, E, F, G	S, T, V, X, Y, Z	3–90	c	2–250
Squeeze roll	A, B, C, D, E, F	R, S, T, U, V, X, Y	30–700	100–5000	25–125
In situ polymerization	A, B, C, D, E, F, G	Y, Z	undetermined	liquid or vapor	6–2.5
Powdered resin	A, B, C, E, F, G	Q	3–60		25–250[c]
Electrostatic spray		Q			20–75[c]
Fluidized bed	E, G	Q			200–2000[c]

[a] Key: A = woven and nonwoven textiles; B = paper and paperboard; C = plywood and pressed fiberboards; D = plastic films and cellophane; E = metal sheet, strip, or foil; F = irregular flat items; G = irregularly shaped

[b] Key: Q = powdered resin compositions; R = aqueous latexes, emulsions, dispersions; S = organic lacquer solutions and dispersions; T = plastisol and organosol formulations; U = natural and synthetic rubber compositions; V = hot-melt compositions; W = thermoplastic masses; X = oleoresinous compositions; Y = reacting formulations, e.g., epoxy and polyester; Z = plastic monomers

[c] Dry thickness.

Extrusion coating is the process of applying a thin bonded film of a plastic to a continuous substrate (web) such as paper, board, foil, fabric, as well as a plastic. A high melt temperature is employed with a downwardly directed slit die to produce a low viscosity melt web that adheres to the substrate (Figure 5.15). The plastic must adhere well to the substrate and exhibit good sealing properties. If necessary, the substrate may be given a pretreatment to improve adhesion.

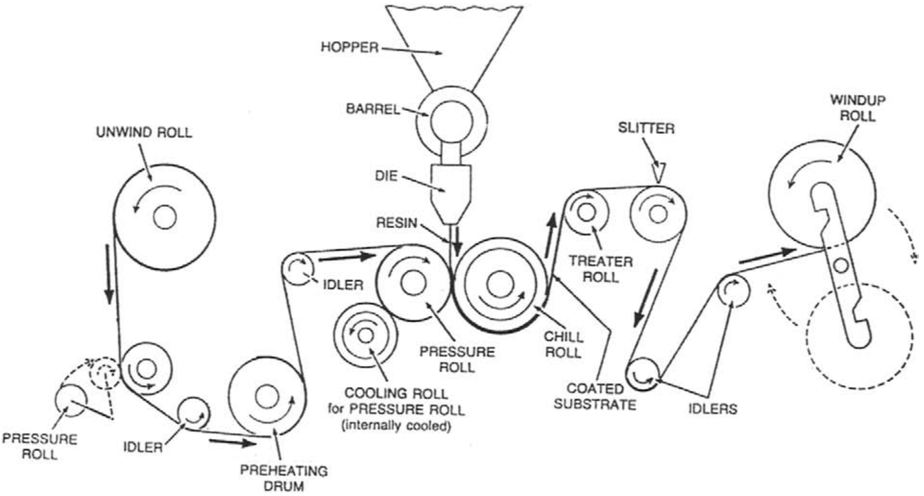

HOPPER
BARREL
UNWIND ROLL
DIE
RESIN
SLITTER
WINDUP ROLL
IDLER
TREATER ROLL
CHILL ROLL
PRESSURE ROLL
COOLING ROLL for PRESSURE ROLL (internally cooled)
COATED SUBSTRATE
IDLERS
PRESSURE ROLL
IDLER
PREHEATING DRUM

Figure 5.15 Coating extruder line highlights the hot melt contacting the substrate just prior to entry into the nip of the pressure-chill rolls

The extruder is on a movable track or platform. On start-up the extruder is in the retracted position, that is the die is not over the web and its operating mechanism. Reason for this pull back is to permit the extruder's start up away from the web and its mechanism. Thus the web and its mechanism is not contaminated with the initial poor grade melt that has to exit the extruder. After the melt develops the desired melt the extruder is moved forward so the die is in the proper position to drop its curtain exactly where required.

In this process the plastic is directed against the surface of the substrate immediately before its entry into the nip between a pressure roll and a chill roll. The extrusion rate and the line speed of the substrate determine the coating thickness. The chill roll controls the surface finish of the coating. Extrusion coatings are typically applied in thin layers, ranging down to 0.005 mm.

A coating can be applied to a substrate and in turn another substrate applied to the coating producing a laminated product. Laminating involves combining two or more substrates together by literally bonding them together with a material such as a plastic coating.

The coating process itself tends to be complex since it contains many controllable variables where each, as well as their interrelation, affects the quality of the coated or laminated product. In general, the processing temperature used in extrusion coating is higher than those in the other extrusion processes. Melt temperatures for the conventional plastics are normally 288 to 300C (550 to 575F). The higher temperatures are required to affect adhesion to the substrate. This higher temperature puts the plastics closer to being degraded.

One of the problems encountered in extrusion coating is that of beading at the edges of the hot film where neck-in occurs (5.8) after the extrudate leaves the die opening. This local thickening of the film has to be removed during the trimming operation. Otherwise when the roll is wound up, the beads at either end only support the weight of the roll, leaving a loosely wound and sagging roll in the middle. The extra trimming required means a reduction in the usable web width thus increasing the costs (this situation relates to the problems reviewed for film).

From unwind to rewind rolls, there are a number of rolls over which uncoated and coated substrates travel. They are necessary to guide the web at an accurate position through the line. The rolls are running in ball or other type bearings that are precision ground. They must be kept clean and accurately fitted into the line on sturdy frames. They are kept in a perfect alignment in the line. When the substrate is a very light or a smooth material, it is frequently necessary for several of the rolls to be driven. For paper however, most auxiliary rolls are idlers.

Because the extrusion coating process requires such a high operating temperature, shutdown requires special considerations and care. One can not just flip a switch for an immediate shutdown. This approach would probably result in degraded plastic in the extruder through to the die. Probably the usual approach to purging would not be adequate. At the time it is planned to shutdown the complete line, the extruder is pulled away from over the coating line. At that time, the coating line is shutdown by releasing or opening rolls, such as the pressure and chill rolls, with probably coated material in the system so it can be used for startup. Keep pumping plastic through the extruder while reducing the temperature from the usual running at 370C (700F) to 260C (500F). When the temperature has reached 260C (500F), it is time to turn off the extruder. At that temperature, the plastic is not usually subjected to rapid, degrading oxidation with its usual formation of hard, discolored plastics that adheres, with exceptional strength, to any adjoining metal.

Wire and cable

From the very beginning of the electrical industry, plastics have been used for their insulation, semiconductivity, and jacketing capabilities. Different plastics are used to meet different performance requirements that include electrical, mechanical, chemical, thermal, and/or environmental. Different conditions exist for each of these categories such as operating at different frequencies, underground, ocean depths, etc. Extensive amounts of different grades of PVC and PE plastics are used. The PEs include low to high density compounded grades, crosslinked grades, and dry swellable grades that prevent water penetration.[201]

Electrical insulation is of major importance to the plastic industry. Large quantities of plastics have been consumed which literally have covered many billions of miles worldwide. As shown in Figure 5.16 a wire extrusion line requires different equipment to operate. The line starts with a wire or cable unwinding roll followed with a tension controlled input capstan, possibly a wire straightener, and wire preheater. The wire proceeds through the usual extruder's 90° crosshead die where the plastic coating is applied. It continues through water and/or air cooling system for TPs or a heating system for thermosets (TSs). Other equipment includes electrical tester, gauge controller, tension output capstan, tension controller, and the windup roll. There is also special equipment included for use with certain plastics, such as nylon, to maximize their performance (toughness, stress relaxation, etc.) by using in-line annealing and moisture conditioning equipment. Variations in

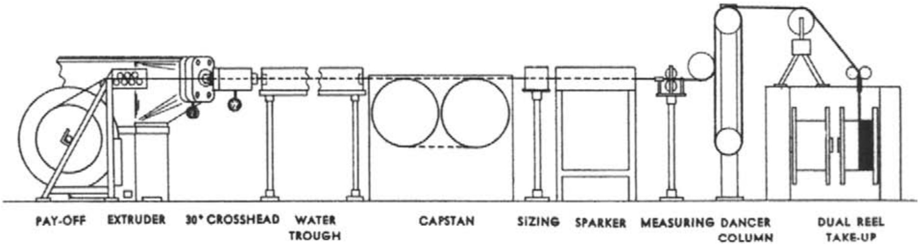


Figure 5.16 Example of a wire coating extrusion line

extruder and plastic performances, such as melt index (MI), influence output and properties of the insulation.

Multi-layer insulation constructions are used. With the high-voltage cable, three separate layers may cover the center conductor. The innermost layer will function as an electric screen, the intermediate layer is usually a PE insulation material, and the outer layer serves as an electric screen. The processing technique can be used for primary and secondary coating where the covering is on metallic conductors or coating previously insulated wires.

The usual die used is a crosshead with a 90° angle between the wire line and the extruder body axis (Chapter 17). With this setup, the entire length of the extruder projects sideways from the coating lines. To help melt flow from developing dead spots in the melt channels, 30° or 45° crossheads can be used. They provide a more streamlined interior and the extruder location is better adapted to some plant layouts. They are sometimes preferred when processing PVC because of the streamlining and better control of the melts heat profile. Most dies are subjected to very high internal pressures since the uncommon pressure in the extruder barrel of over 5,000 psi (35 MPa) is required.

As explained in Chapter 17 die configurations meet certain melt flow requirements such a drawdown ratio and draw ratio balance. Draw-down ratio (DDR) in a circular die, such as a wire die, is the ratio of the cross sectional area of the die orifice/opening to the final extruded shape. Another guide for setting uniformity and best repeatable references is the draw ratio balance (DRB) that aids in determining the minimum and maximum values that can be used for different plastics.

An example of an exception to the use of a screw operating extruder occurs when a very low melt plastic such as PTFE (polytetrafluoroethylene) is to be used where its specialty properties are needed. PTFE does not easily melt, particularly in the production of heavy wall PTFE wire coatings, so ram extrusion is used. Ram extrusion is used for these wire and cable jobs and also for producing rods, tubes, and large round solid "cakes" that are later skived to make PTFE film.

With developments in equipment and the fluoropolymers that have high melt viscosities, the maximum extrusion rate using screws is normally limited by melt fracture. However, these plastics have exceptional melt strength. This characteristic makes possible ram extruding using a die with a large opening and apply a draw down of the extrudate to the desired insulation thickness.

Other processing systems are used to meet different property and/or cost requirements of TS plastics. As an example vulcanization is used to cure different type TS elastomers/rubbers such as SBR, IR, and CR (neoprene). Methods of vulcanization or curing include steam, liquid (eutectic mixtures), microwave, and hot air. There are systems used to cure peroxide-based cross-linkable polyethylene (XLPE) compounds. They include steam cure, nitrogen cure, and pressurized liquid continuous vulcanization (CV). All these methods involve higher heat than the melt heat to cause the peroxide in the plastic to decompose into a reactive radical and initiate the curing cycle.[143, 202]

Fiber

The term fiber basically refers to filamentary material and is often used synonymously with filament, monofilament, whisker, and yarn. A filament is the smallest unit of a fibrous material and is usually not used alone. It can be identified as any material in a form such that it has a minimum length of at least 100 times its diameter. Diameters are usually 0.004–0.005 in. (0.10–0.13 mm). They can be continuous or reduced to short lengths (discontinuous). The industry lists fibers as having a specific length, such as 0.125 in. (3.2 mm).

Filaments are the basic units formed during manufacture that are gathered into strands of fiber. Their diameters are less than 0.001 in. (0.025 mm). Its denier also identifies the fineness of a fiber. Denier is a unit of weight expressing the size or coarseness but particularly the fineness of a continuous fiber or yarn. The denier number represents the weight in grams of 9000 meters of yarn, and is a measure of linear density. The weight in grams of 30,000 ft (9000 m) is one denier. The lower the denier, the finer the fiber, yarn, etc. As an example sheer women's hosiery usually runs from 10 to 15 denier. An alternative unit is the tex, representing the weight in grams of 1000 meters. Yarn linear density is sometimes expressed in decitex where 1 dtex = 0.1 tex. There are different fiber products such as staple fibers that will be reviewed.

Just in the USA during 2001, the man-made plastic fiber industry had over 90 plants with sales of $13 billion and employed about 45,000 people. Fabrication processes are diverse both in technology and equipment design. They have common steps that include preparation of reactants, polymerization, plastic recovery, plastic extrusion, and supporting operations. In some preparation operations, solvents are used to dissolve or dilute monomer and reactants. Solvents are also used to facilitate the transportation of the reaction mixture throughout the plant, to improve heat dissipation during the reaction, and to promote uniform mixing. Solvent selection is optimized to increase monomer ratio and to reduce polymerization costs and emissions. The final polymer/plastic may or may not be soluble in the solvent.

Dry spinning involves a solution of plastics. The solution is then heated above the boiling temperature of the solvent and the solution is extruded through a spinneret. The solvent evaporates into the gas stream. With wet spinning, the fiber is directly extruded into a coagulation bath where solvent diffuses into the bath liquid and the coagulant diffuses into the fiber. The fiber is washed free of solvent by passing it through an additional bath. Each process step generates emissions or wastewater. Solvents used in production are recovered by distillation.

Extruders have their part in producing fibers or filaments. There are many variations and combinations of the basic processes that include:

1 reaction spinning;
2 dispersion, emulsion, and suspension spinning;
3 fusion-melt spinning;
4 phase-separation spinning;
5 gel spinning.

During processing, molten melt spinning plastic is forced by just a gear pump or an extruder through fine holes in a spinneret die (Figure 5.17). The spinneret holes may be simple cylindrical bores but may also be profiled to create fibers with improved wicking properties. Common profiles include trilobal, quadrilobal, delta, and dogbone shapes. The land length of the spinneret holes is typically in the range 5 to 15 times the hole diameter. In turn they are immediately stretched or drawn (oriented), cooled, and collected at the end of the line. During this process they may be subjected to other operations such as:

1 thermal setting and thermal relaxation processes to provide dimensional stability;
2 twisting and interlacing to provide cohesion of the filaments with or without sizings;
3 texturing;
4 crimping and cutting to provide staple products.

Speeds of certain lines using the melt and dry spinning processes can go from 2,000 m/min (6,600 ft/min) to at least 4,000 m/min (13,000 ft/min).

The spinneret passes the melt through a very large number of very small holes. It is a rectangular plate die, typically provided with 200 or

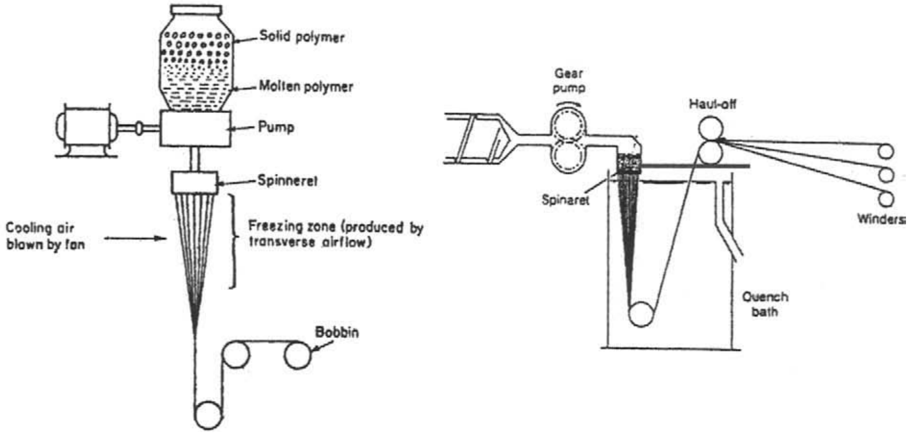


Figure 5.17 Example in using a gear pump to produce fibers (left) and example in using an extruder and gear pump to produce fibers

more holes arranged in a grid formation. This action gives the process a number of distinctive features. The process demands a low melt viscosity. High melt flow index grades are used, and at relatively high melt temperatures in the range of 230C to 260C. Because the holes in the spinneret are very small, an exceptionally high degree of melt filtration is necessary to screen out foreign particles that would otherwise clog the spinneret or cause the filament to fracture in the stretching operation.

This system of extrusion does not have the die mounted at the extruder outlet, the fiber-forming spinneret is mounted at some distance from the extruder and is connected to it by a heated melt manifold system. From the extruder, the melt stream passes through a filter system. As the melt emerges from the spinneret hole, it passes down a spin chimney where it is cooled or quenched in streamline airflow operating at a controlled temperature and then hauled off by godet rolls. The final step is yarn stretching or drawing to orient the molecular chains to a high degree in the machine direction. Orientation also reduces the diameter of the fibers. The process is performed at a temperature close to but less than the melt temperature, by stretching between rolls operating at a speed differential. The orientation is set by an annealing step and the continuous filament yarn is wound on spools or bobbins for subsequent use in textile operations.

During fiber spinning they can be exposed to different conditions. Different type finishes can be applied after cooling in-line to meet different requirements that include permitting processing improvement during weaving, handling of fibers, etc. Texturing introduces crimp, whereby the straight filaments are given a twisted, coiled, or randomly kinked structure. A yarn made up of these filaments is softer and more open in structure; it is more pleasing to the touch.

Fibers are twist during fabrication. The twist is the spiral turns about its axis per unit of length. Twist may be expressed as turns per inch (tpi). The letters S and Z indicated the direction of the twist, in reference to whether the direction conforms to the middle-section slope of the particular letter.[143] A fiber, yarn, or strand has what is known as an "S" twist if, when held in a vertical position, the spirals conform in slope to the central position of the letter S. It has a "Z" twist if the spirals conform in slope to the central portion of the letter Z. Fibers that are simply twisted (greater than 1 turn/in. or 40 turns/m) will kink, corkscrew, and/or unravel because their twist is only in one direction. The plying operation normally eliminates this problem. For example single yarns having a "Z" twist are plied with an "S" twist, thus resulting in a balanced yarn. Depending on the twisting and plying operations, different yarn strengths, diameter, and flexibility can be obtained. This action provides the different shaped and handling fabrics that are used to meet different performance requirements of plastic materials such as coated fabrics, reinforced plastics, pultrusions, etc.

Monofilament yarns consist of a single filament. The filament size is much larger than those found in multifilament yarn. Consequently, monofilament is relatively stiff and is used mainly for the production of rope and twine. Fiber size range is typically 75 to 5000 denier. Monofilament fiber is usually produced from polypropylene homopolymer with a relatively low melt flow index in the range 3.5 to 5.0 grams/10 min.

Extruded cast film can be slit into narrow tapes that are then uniaxially oriented in the machine direction becoming slit filament. The chill roll may cast the film or water quenches processes. The slit film fiber (plain tape) may be used as it is in weaving processes, or it may be given a subsequent fibrillation treatment to impart a fibrous character. Slitting occurs with the film in tension upstream of the first set of godet rolls that anchor the tapes ahead of the orientation oven. A second set of godet rolls applies a stretching tension to the tapes that are heated to a temperature just below the melting point. Draw ratios typically range from 1:5 to 1:8. Heated rolls may be used as an alternative to the draw oven. In the final step in this operation the tapes are annealed to set the orientation, and are wound on spools for subsequent use in textile operations.

Similar to slit film fiber, fibrillated tape fiber is produced. However a draw ratio of up to 1:10 is used and a fibrillation step is added to the process. The slit film tapes are fibrillated by passing them over a rapidly rotating roll fitted with staggered rows of pins. As the pins are traveling faster than the tapes, they make a series of short discrete cuts in the longitudinal direction of the tapes.

Bulked continuous filament yarn is produced in exactly the same manner as continuous filament but is given an additional treatment before final spooling. The purpose of this treatment is to improve the handling, feel, and elasticity of a textile article manufactured from the yarn. There are a number of different bulking treatments, the target always being to produce minor distortions to the filaments. The principle is to heat the yarn close to the melting point by means that perturb the filaments, using steam jets, turbulent hot air, or a hot knife-edge.

There is staple fiber that consists of intermingled short length multi-filament fibers similar to natural fibers such as wool or cotton. They are produced in much the same manner as continuous filament but the filaments are finer and are collected together in large numbers in a loose rope or tow. The spinneret contains a very large number of holes such as 15,000 or more and sometimes ranging as high as 50,000. The tow is passed through a crimper that imparts a small zigzag configuration to the filaments and is then chopped into short lengths from 5 to 60 mm. The chopped fibers are baled in random orientation for use in any textile process conducted with staple fiber.

Coextrusion

The different extrusion processes (film, profile, etc) using coextrusions that can range from two to seven or more layers are not uncommon (Chapters 3 and 17).[203, 204, 205] An example for just coextruding film or sheet is shown in Figure 5.18. Coextrusion is an economical competitor to conventional laminating processes by virtue of its reduced materials handling costs, raw material costs, and machine-time cost. Pinholing is also reduced with coextrusion, even when it uses one extruder and divides the melt into at least a two-layer structure. Other gains include elimination or reduction of delamination and air entrapment. It provides an excellent way to integrate/entrap recycled contaminated plastic with one side or both sides using virgin plastic. It provides combining the different properties of the different plastics that result in performance and cost advantages.

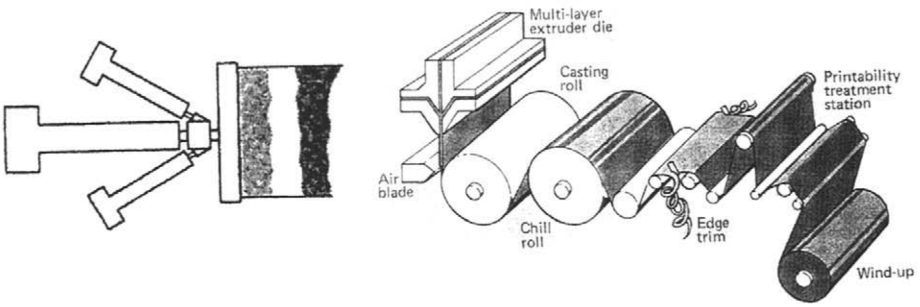


Figure 5.18 Schematic of a basic three layered coextrusion sheet or film system

The different materials used in the coextruded structure meets different performance requirements such as strength, stiffness, toughness, noise absorption, resist permeation (air, oxygen, moisture, gas, odor, etc.), adhesive qualities, and economics. A single expensive plastic could be used to meet performance requirements, however it is possible to provide combinations of plastics to reduce the cost. An example as used in the marketplace; coextrusion has been adapted to the production of products like building profiles, pipes, and packaging films that incorporate in a single extrusion structure several layers of different plastics, each offering varying degrees of different performance requirements.

Compatible plastics can flow through a single manifold reducing any potential problem down-stream in the multimanifold. Combinations can be made to provide different laminated designs. However, the final exiting layer thickness distributions can be affected by the amount of die body deflection if the die is not properly designed to take the required pressure loads. Any deflection causing distortion influences the melt flow channels (Chapter 17).

Many plastics can be bonded to each other. There are those that require a tie-layer. Choosing an adhesive tie-layer is by no means a simple operation as in coinjection (Chapter 4). There are many different types, each with specific capabilities. EVAs form the bulk being used. Proper choice can improve performance, such as increasing melt strength and bubble stability in blown film. High melt strength can also help in cast film used in thermoforming or coating. Good melt draw is required to run higher take-up speeds and or thinner structures without causing flow distribution or edge-weave problems.

Melt flow instabilities, such as interfacial instability, melt fracture, surging, and/or layer nonuniformity, can become problems that could cause quality problems with the coextruded product.[200] There are several options to correct these problems. The key to success is to select the best option or combination of options to eliminate the problem and minimize other possible adverse effects. Flow instabilities can cause limited production rates. Appropriate operating conditions of the coextrusion process combined with the proper plastic selections can successfully be used to solve the problems.

Orientation

Orientation consists of a controlled system of stretching TP molecules in unioriented [unidirectional (UD)] or bioriented [biaxial direction (BD)]. UD orientation can be in the machine direction (MD) or transverse direction (TD).[207] Orientation improves strength, stiffness, optics, electrical, and/or other properties with the usual result that improved product performance-to-cost occur. This technique is used during the processing of many different products such as films, sheets, pipes, fibers, tapes, etc.

Depending on the properties of a specific plastic product the stretch ratio may vary from 2½:1 to as high as 10:1. Some specialty films may have an even higher stretch ratio. Used for almost a century, it became prominent during the 1930s for stretching fibers up to 10 times. Later it was adapted principally to films and other products such as stretched blow molded bottles. Practically all TPs can undergo orientation, although certain types find it particularly advantageous (PET, PP, PVC, PE, PS, PVDC, PVA, PC, etc.). Many different markets use oriented plastic products. The largest market for plastics worldwide, consuming about 20wt% of total, is oriented plastic film.

Orienting by stretching is influenced by factors such as:

1 the lowest temperature will give the greatest orientation (tensile strength, modulus, etc.)

2 the highest rate of stretching will give the greatest orientation at a given temperature and percent stretch

3 the highest percent stretch will give the greatest orientation at a given temperature and rate of stretching,

4 the greatest quench rate will preserve the most orientation under any stretching condition.

With orientation, the thickness is reduced and the surface area enlarged. If film is longitudinally stretched, its thickness and width are reduced in the same ratio. If lateral/transverse contraction is prevented, stretching reduces the thickness only. Orientation temperature is normally 60 to

75% of the range between the plastic's glass transition temperature (T_g) and melting point (T_m). Equipment can be used in-line or off-line to gain output yield and properties.

Examples of many oriented products include the heat-shrinkable material found in flat or tubular films or sheets and fibers. The orientation in these cases is terminated downstream of an extrusion-stretching operation when a cold-enough temperature is achieved. Reversing the operation, shrinkage occurs when a sufficiently high temperature is introduced. The reheating and subsequent shrinking of these oriented plastics can result in a useful property. It is used, for example, in heat-shrinkable flame-retardant PP tubular or flat communication cable wraps, heat-shrinkable furniture webbings, pipe fittings, medical devices, and many other products.

Mechanical properties depend directly upon the relationship between the axis of orientation of the plastic molecules and the axis of mechanical stress upon the molecules. Modulus, strength, etc. increases in the direction of stretch and decreases in the perpendicular direction. This is the mechanism of pseudoplastic and thixotropic rheology typical of a non-Newtonian plastic flow behavior. After processing, some loss in properties may occur (insignificant) when subjected to heat during further processing, such as thermoforming, heat sealing, and solvent sealing.

Biaxial orientation of crystalline plastics generally improves clarity of films. This occurs because stretching breaks up large crystalline structures into smaller than the wavelength of visible light. With uniaxial orientation, the result is an anisotropic refractive index and thus birefringence, especially in crystalline plastics.

Orientation decreases electrical dissipation factors in the direction of the orientation, and increase occurs perpendicular to orientation. Since modulus changes in the opposite way, this indicates that polar vibrations along a stretched plastic molecule are decreased, while transverse vibrations between the stretched molecules are increased.

Different methods are used. An online ordinary common blown or cast film line uses a machine direction orienter (MDO) on the front end of biaxially oriented film heated chamber extrusion line. If only the machine direction is to be stretched, a series of precision controlled heated rolls can be used. Film is fed through a series of rolls where it is sequentially heated, drawn around rolls that increase in rotational speed providing the stretching action, annealed around larger diameter roll(s), and cooled on a final roll(s).

A TP's molecular orientation can be accidental or deliberate. Accident can occur during the processing of TPs where excessive frozen-in stresses develop, however with the usual proper process control, there is no accidental orientation (Chapter 3). The frozen-in stresses with certain TPs can be extremely damaging if products are subjected to stress cracking in certain environments, crazing in the presence of heat or chemicals, etc. Initially the molecules are relaxed. Molecules in the amorphous regions are in random coils; those in crystalline regions are relatively straight and folded.

During processing (extrusion, injection, blow molding, etc.) the molecules tend to be more oriented than relaxed, particularly when the melt is subjected to excessive shearing action. After temperature-time-pressure is applied and the melt goes through restrictions (mold, die, etc.), the molecules tend to be stretched and aligned in a parallel form. The result can be undesirable changes in the directional properties and dimensions immediately when processed and/or thereafter when in use if stress relaxation occurs.

By deliberate stretching, the molecular chains of a plastic are drawn in the direction of the stretching, and inherent strengths of the chains are more nearly realized than they are in their naturally relaxed configurations. Stretching can take place with heat during or after processing by extruding film, blow molding, injection molding, thermoforming, etc. Products can be drawn in one direction or in two opposite directions, in which case many properties significantly increase uniaxially or biaxially.

The amount of change depends on the type of TP, the amount of restriction, and, most important, its rate of cooling. The faster the rate, the more retention there is of the frozen orientation. After processing, products could be subject to stress relaxation, with changes in performance and dimensions. With certain plastics and processes there is an insignificant change. If changes are significant and undesirable, one must take action to change the processing conditions during and/or after processing. As an example during processing increase the cooling rate. Annealing of the product is an after processing condition approach.

The processing hardware of orientation is fairly expensive. It increases the cost per unit weight of the product. However, the yield increases considerably, its quality improves greatly, and the product cost reduction occurs. Many products are made much stronger, flexible, tougher, etc. resulting in significant cost advantages.

Blown Film

The blown products, such as upward blown film, are basically natural for providing orientation (Figure 5.19). The blow-up ratio determines the degree of circumferential orientation, and the pull rate of the bubble determines the longitudinal orientation.

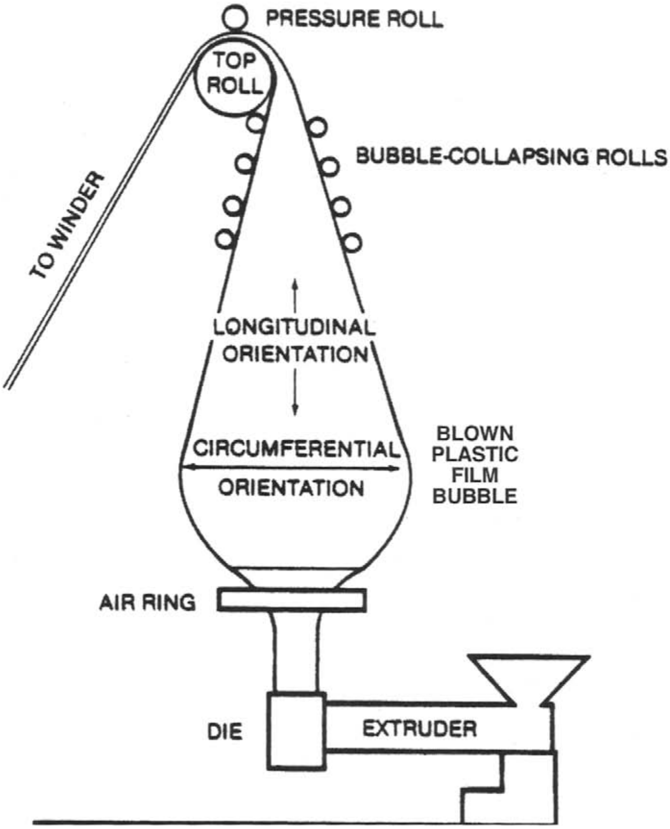

PRESSURE ROLL
TOP ROLL
BUBBLE-COLLAPSING ROLLS
TO WINDER
LONGITUDINAL ORIENTATION
CIRCUMFERENTIAL ORIENTATION
BLOWN PLASTIC FILM BUBBLE
AIR RING
DIE
EXTRUDER

Figure 5.19 Example of upward extruded blown film process for biaxially orienting film

The optimum stretching heat for amorphous plastics (PVC, etc.) is usually just above its glass transition temperature (T_g; Chapter 1). Generally the orientation temperature is 60 to 75% between the T_g and T_m (melt temperature). For crystalline plastics (PE, PET, etc.) generally it is below the T_g. Stretching can take place in-line or off-line with or without tenter frames using the appropriate temperature-pull rates as the plastic travels first through a series of heated rolls. For unidirectional orientation just the rolls are used.

In addition to the upward blown film there is also the downward extrusion. It allows the tube to be quenched rapidly in a water bath after which it is collapsed as a layflat for passage over nip and idler rollers.

Film passes through a reheating tunnel where it is raised to a temperature above the softening point but below the melting point. The heated tube is then inflated by internal air pressure that forms a bubble in which the film is stretched in all directions. Some machine-direction stretch may take place in the ovens upstream of the bubble; the haul-off rate can be adjusted if necessary to secure an orientation balance. An air ring similar to that used in other blown film processes provides bubble cooling. Subsequent calibration and bubble collapsing operations are also similar.

Flat Film

Using some type of tenter frame can biaxially orient flat products. Orienting film is accomplished by mechanically stretching the film in the tenter machine. This takes its name from the tenter frame originally used for stretching cloth between grips known as tenterhooks. Simultaneous tentering is possible, involving complex movements of the film edge grips so that the film is stretched in the machine and transverse directions at the same time. However, the process can be mechanically complicated and can be difficult to adjust the balance between the stretch directions for certain plastics. To eliminate potential problems the two-step tenter process is used (Figure 5.20). The process starts with the production of a cast film. This is then stretched in the machine direction by passing it around heated rollers rotating at controlled and increasing speeds in excess of the extrusion output speed. Varying the roll speeds controls the degree of stretch. Typically, stretch in the machine direction is about 4.5:1.

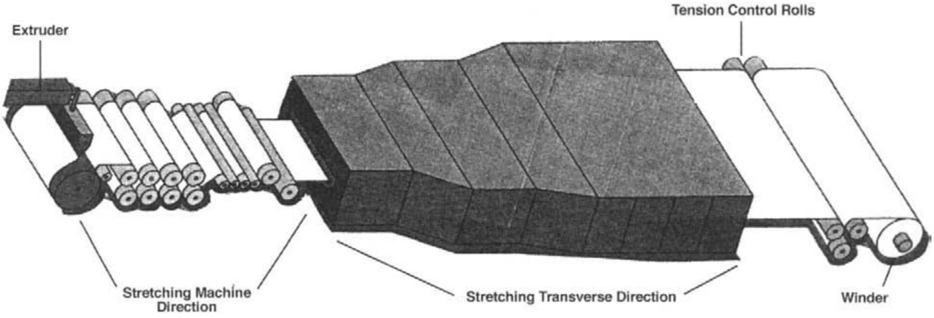


Figure 5.20 Example of two-step tenter process

When machine direction stretching is complete, the tenter machine applies transverse stretching. This consists essentially of a temperature-regulated tunnel in which the film edges are gripped by chain-driven tension clips running on divergent paths. As the film passes through the tunnel it is progressively stretched in the transverse direction as the clips diverge. The edge grip mechanism must withstand high cross loads of up to 3.5 kN per clip, and be capable of operating at line speeds of up to 450 m/min. Transverse stretch is controlled by varying the divergence of the edge clip paths. A ratio of 8:1 is typical. Feeding the orientation system can be from an extruder or an extruded roll of film.

Fiber

It is accomplished usually by just stretching when the fibers are produced. They can also be stretched by a set of heated rolls where each of their rotating speeds (rpm) are increased. A fiber or thread of nylon 6/6, that is an unoriented glassy polymer, has a modulus of elasticity of about 2,000 MPa (300,000 psi). Above the T_g (glass transition temperature) its elastic modulus drops even lower, because small stresses will readily straighten the kinked molecular chains (Chapter 1). However, once it is extended and has its molecules oriented in the direction of the stress, larger stresses are required to produce added strain. The elastic modulus significantly increases.

The next stop is to cool the nylon below its T_g without removing the stress, retaining its molecular orientation. The nylon becomes rigid with a much higher elastic modulus in the tension direction [15,000 to 20,000 MPa (2 to 3 × 10^6 psi)]. This is nearly ten times the elastic modulus of the unoriented nylon-66 plastic. The stress for any elastic extension must work against the rigid backbone of the nylon molecule and not simply unkink molecules.

Other process

Different processes take advantage in applying orientation to gain certain properties in certain products. Major product lines include stretched blow molded bottles/containers (Chapter 6), thermoformed oriented containers (used for such products as fruits, vegetables, and baked goods) (Chapter 7), tapes, etc.

Postforming

There is off-line (for small quantity of products) or in-line postforming. The in-line refers to forming/shaping the extrudate (tube sheet, etc.) just after it emerges from the extruder die but before the plastic has a chance to cool. It provides specialty products with performance and cost advantages. Upon leaving the extruder's die and while it is retaining its heat, the plastic is continually post-formed producing products such as embossing patterns on flat, twisted, curved, etc. shapes.[208] Also coiled form of tube, rod, profile, etc.; twisting different extrudates; and small or large (up to at least 6 ft) corrugated tubing or piping. Examples of these type actions are shown in Figure 5.21.

Compounding

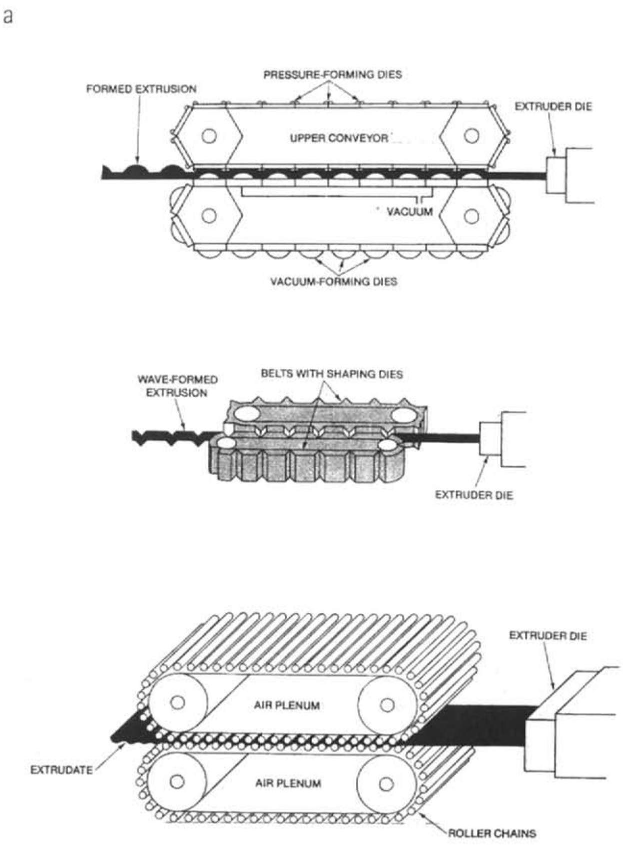
Compounding deals with mixing and dispersing additives, fillers, pigments, stabilizers, reinforcing agents, antioxidants, inhibitors, foaming agents, processing aids, etc. into a melted polymer by different equipment (Figures 5.22 and 5.23). Of major importance are single and multiscrew extruders with the multiscrews most important. Each type extruder provides different capabilities. As an example the twin and multiscrews produce excellent mixing by forcing the melt back and forth from one screw to another. This breaks up the flow patterns. Venting of the extruder also is efficient with the dual screw giving good exposure of the plastic in the vent zone. Often twin-screw extruders have self-wiping screws, which can be purged rapidly and efficiently. Some of these extruders are designed to be extra gentle with respect to mechanical working of the plastic. They are used to give a low melt temperature and very little decomposition of the plastic.[209]

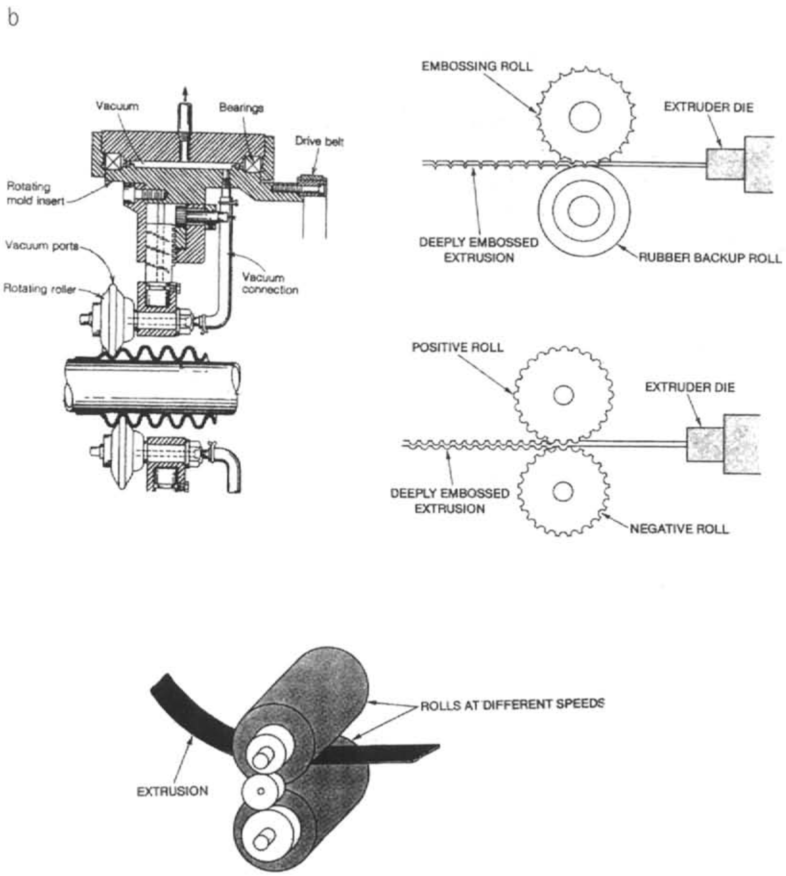
Single-screw extruders for compounding have relatively long L/D ratios (from 32:1 to 40:1), usually with several barrier sections Venting is almost always employed to remove the molten polymer of unwanted vapors (Chapter 3).

Corotating intermeshing twin-screw extruders are frequently used in compounding. Nonintermeshing screws are used in devolatilizing extruders where very large surface area renewal is required to allow for diffusion of unwanted vapors from the melt. Intermeshing conical counter-rotating screw machines are most often used for compounding of PVC. Ko-Kneaders are multiple screw machines featuring rotating shafts that reciprocate in an axial direction. This type of machine is widely used for plastics such as PP and PVC.

Reclamation/recycling

Recycled plastic is used to fabricate products (Chapter 2). Reclaiming plastics can require special equipment because the feedstock for the


a
PRESSURE-FORMING DIES
FORMED EXTRUSION
EXTRUDER DIE
UPPER CONVEYOR
VACUUM
VACUUM-FORMING DIES
WAVE-FORMED EXTRUSION
BELTS WITH SHAPING DIES
EXTRUDER DIE
EXTRUDER DIE
AIR PLENUM
AIR PLENUM
EXTRUDATE
ROLLER CHAINS


b
Vacuum
Bearings
Drive belt
Rotating mold insert
Vacuum ports
Rotating roller
Vacuum connection
EMBOSSING ROLL
EXTRUDER DIE
DEEPLY EMBOSSED EXTRUSION
RUBBER BACKUP ROLL
POSITIVE ROLL
EXTRUDER DIE
DEEPLY EMBOSSED EXTRUSION
NEGATIVE ROLL
ROLLS AT DIFFERENT SPEEDS
EXTRUSION

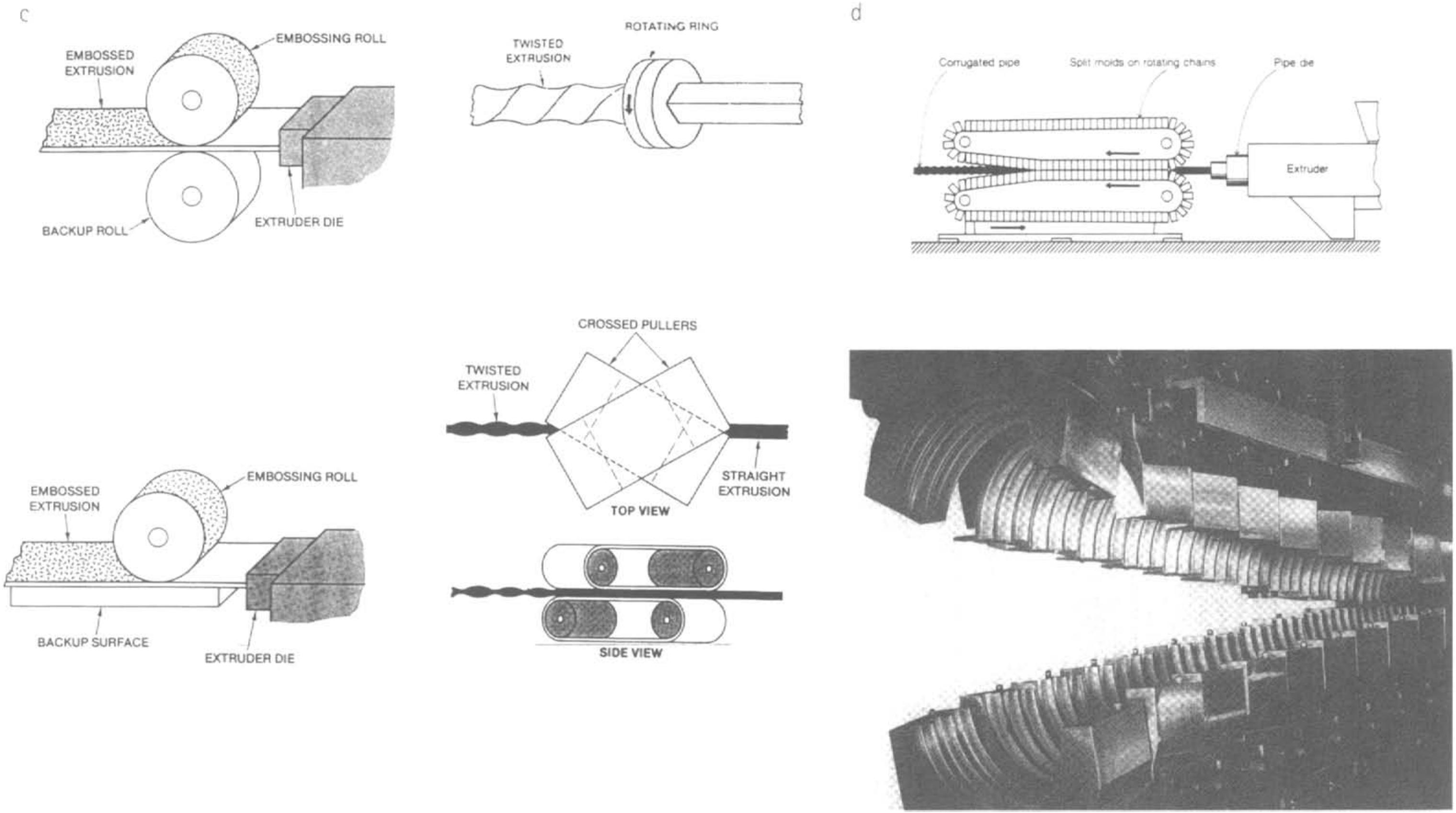
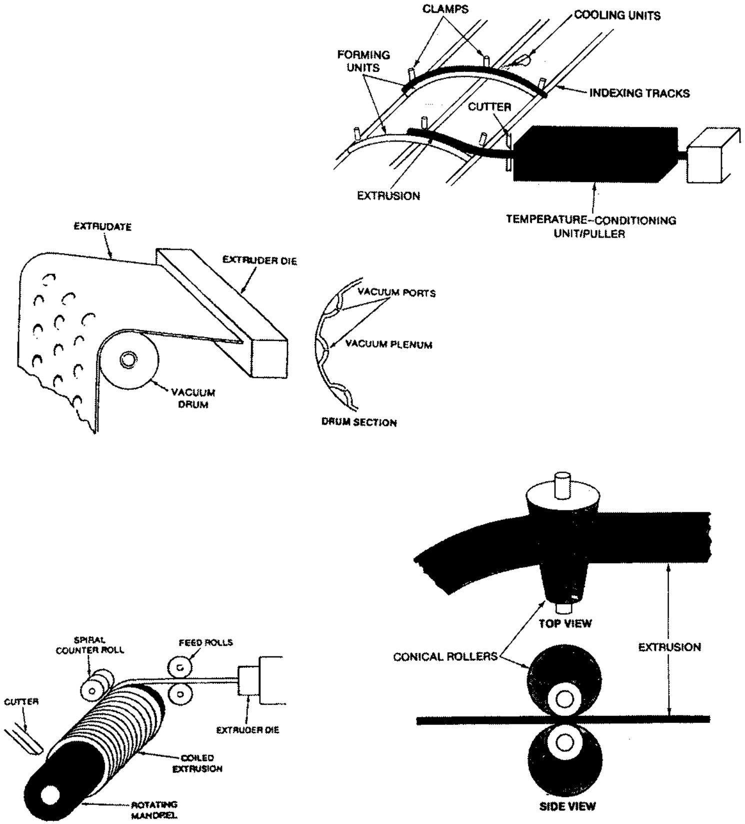

c
EMBOSSED EXTRUSION
EMBOSSING ROLL
BACKUP ROLL
EXTRUDER DIE
TWISTED EXTRUSION
ROTATING RING
EMBOSSED EXTRUSION
EMBOSSING ROLL
BACKUP SURFACE
EXTRUDER DIE
CROSSED PULLERS
TWISTED EXTRUSION
STRAIGHT EXTRUSION
TOP VIEW
SIDE VIEW
d
Corrugated pipe
Split molds on rotating chains
Pipe die
Extruder

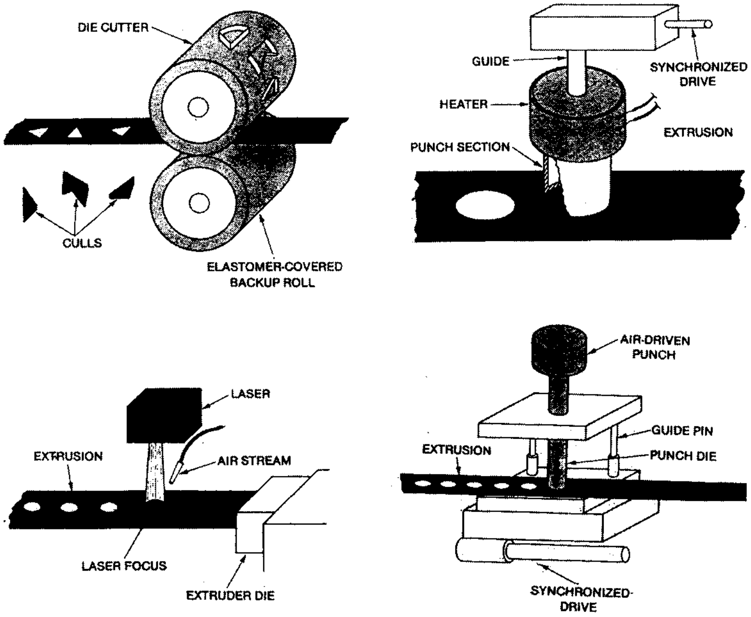
Figure 5.21 Few examples of the many different postformed shapes and cuts with some showing dies

continued

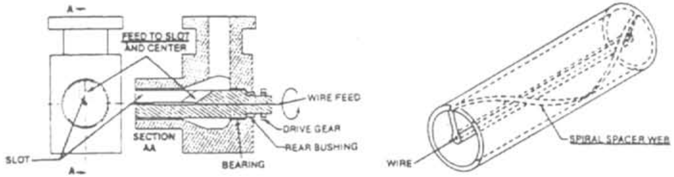
e


CLAMPS
COOLING UNITS
FORMING UNITS
INDEXING TRACKS
CUTTER
EXTRUSION
TEMPERATURE-CONDITIONING UNIT/PULLER
EXTRUDATE
EXTRUDER DIE
VACUUM PORTS
VACUUM PLENUM
VACUUM DRUM
DRUM SECTION
TOP VIEW
CONICAL ROLLERS
EXTRUSION
SIDE VIEW
SPIRAL COUNTER ROLL
FEED ROLLS
CUTTER
EXTRUDER DIE
COILED EXTRUSION
ROTATING MANDREL

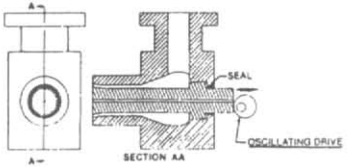
f


DIE CUTTER
CULLS
ELASTOMER-COVERED BACKUP ROLL
GUIDE
SYNCHRONIZED DRIVE
HEATER
EXTRUSION
PUNCH SECTION
LASER
EXTRUSION
AIR STREAM
LASER FOCUS
EXTRUDER DIE
AIR-DRIVEN PUNCH
GUIDE PIN
EXTRUSION
PUNCH DIE
SYNCHRONIZED-DRIVE

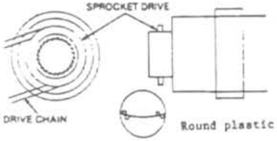
g


A
FEED TO SLOT AND CENTER
WIRE FEED
DRIVE GEAR
REAR BUSHING
SECTION AA
BEARING
SLOT
A
SPIRAL SPACER WEB
WIRE

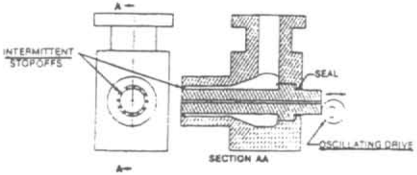
Coaxial cable with a spiral spacer web that keeps coated wire in the center


A
SEAL
OSCILLATING DRIVE
SECTION AA
A

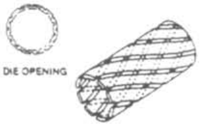
Varying tube wall thickness using an oscillating mandrel in cross head tube die


SPROCKET DRIVE
DRIVE CHAIN

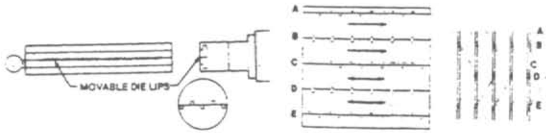
Round plastic netting


A
INTERMITTENT STOPOFFS
SEAL
OSCILLATING DRIVE
SECTION AA
A

Different perforated tubing pattern; using oscillating mandrel die


DIE OPENING

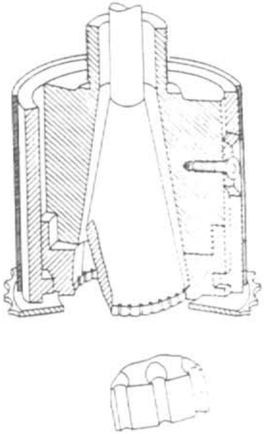
Rotating mandrel die makes perforated tubing

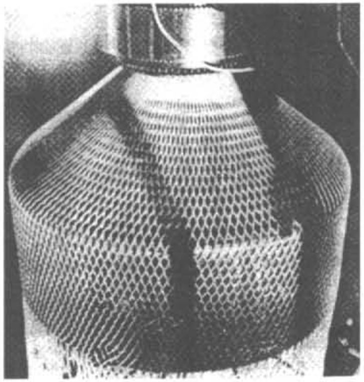

MOVABLE DIE LIPS
A
B
C
D
E
A
B
C
D
E

Flat netting ....with different positions of die lips

Figure 5.21

h





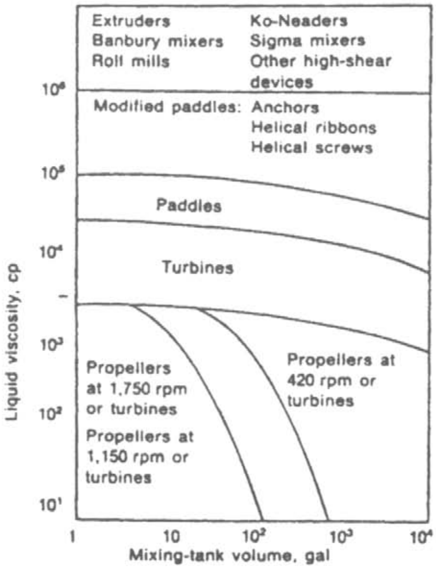


Figure 5.22 Examples and performances of compounding equipment

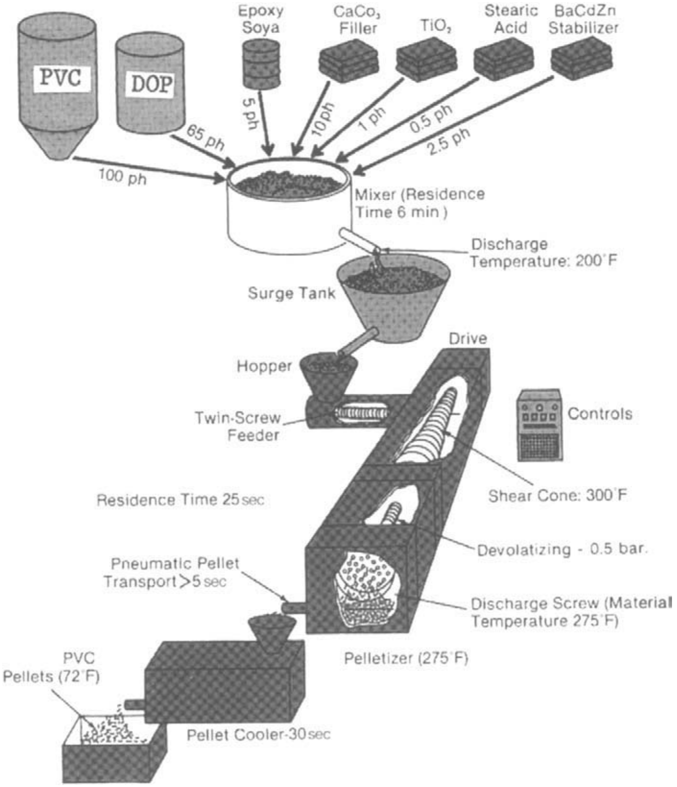

PVC
DOP
Epoxy Soya
$CaCo_3$ Filler
TiO_2
Stearic Acid
BaCdZn Stabilizer
100 ph
65 ph
5 ph
10 ph
1 ph
0.5 ph
2.5 ph
Mixer (Residence Time 6 min)
Discharge Temperature: 200°F
Surge Tank
Drive
Hopper
Twin-Screw Feeder
Controls
Shear Cone: 300°F
Residence Time 25 sec
Devolatizing - 0.5 bar.
Pneumatic Pellet Transport >5 sec
Discharge Screw (Material Temperature 275°F)
PVC Pellets (72°F)
Pelletizer (275°F)
Pellet Cooler-30 sec

Figure 5.23 Schematic of compounding PVC

extruder comes in many forms. Since the bulk density of most of the scrap plastic used is low, a dual-diameter extruder is often used. The feed end of the screw has a larger diameter so there is a greater volume for the entering feedstock. This helps increase production rates. Single-diameter extruders with force feeding capability are also used for reclamation. To improve the performance of many recycled plastics they are subjected to compounding with certain additives such as reinforcements.

6 BLOW MOLDING

Introduction

Blow molding (BM) is a process for converting thermoplastics (TPs) into simple to intricate and complex shapes hollow objects. The process is especially amenable to the goal of consolidating as much function as possible into a single product. Like injection molding, the process is discontinuous or batchwise in nature, involving a sequence of operations that culminates in the production of a molding. The three basic processes are shown in Figure 6.1. BM is a very highly developed process with variant forms.[34, 143, 164, 203, 212, 213, 214, 227, 435]

The process is to inflate a softened TP hollow form against the cooled surface of a closed cool female mold cavity where the plastic solidifies into a hollow product. The surfaces of the moldings are smooth and bright, or as grained and engraved as the surfaces of the mold cavity in which they are processed. Virtually most products require no finishing or secondary operations. BM permits potential of consolidation of parts competing with other processes such as injection molding (Chapter 4).

Applications for BMs are used to contain many different products that include foodstuffs, beverages, household products (appliances, air conditioners, furniture at home/office/hospital/sports arenas, etc.), personal care products, medicine/pharmaceutical products, automotive parts [bumpers, spoilers, air ducts, seat backs, etc.], construction panels, tote boxes, trays, leisure items (toys, floatation, marine buoys, canoes, sailboards, sports goods, etc.), industrial parts (business machines, tool boxes, trash containers, hot water tanks, etc.), and so on.[215–217]

BM is the third largest plastic processing technique worldwide used for producing many different products. It consumes about 10wt% of all plastics. HDPE accounts for nearly 90wt% of the plastic used. PET

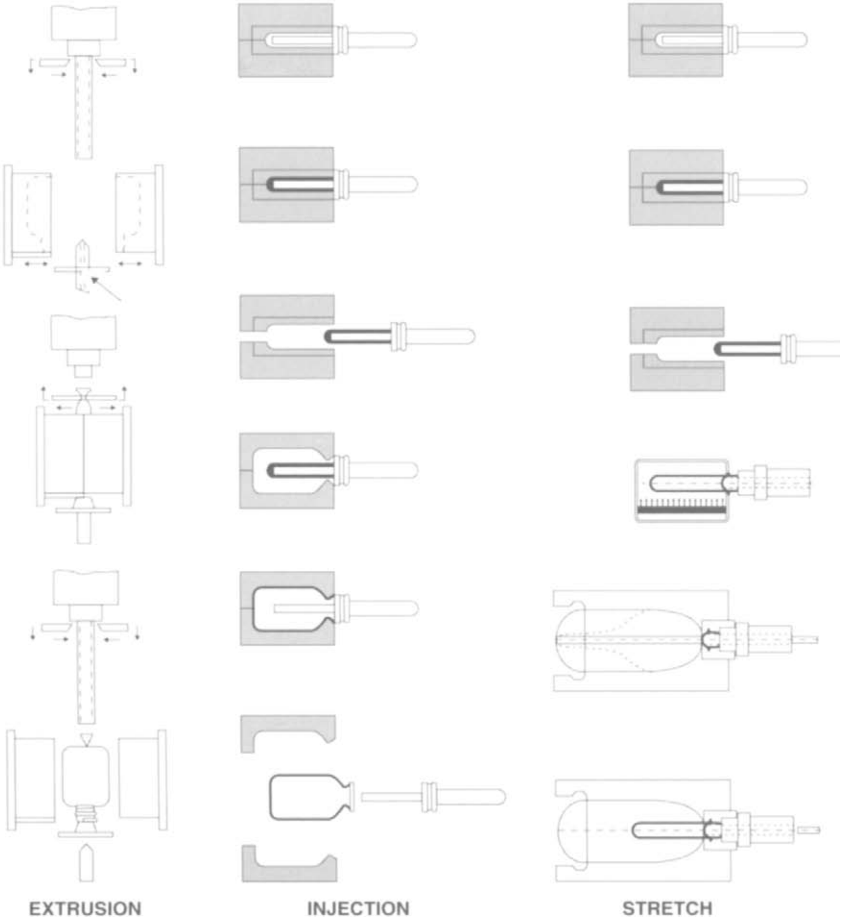


Figure 6.1 Examples of extrusion, injection, and stretch blow molding techniques

plastic in addition to being used in beverage bottles has started to appear in bottles for motor oil and other auto and marine fluids. PET is also being utilized more frequently in containers.

PETs high clarity imparts greater shelf appeal. Growth for PET in food and beverage containers will average 9% to 10%/yr over the next five years, but growth is expected to be only 2% annually for PET industrial BM containers due to HDPE's lower price and greater chemical resistance. If PET can be price-competitive with HDPE, then it is likely that PET will capture market share from HDPE bottles. PVC is losing popularity but is still used in industrial packaging. Automotive and marine fluid bottles are molded of PVC because it provides hydrocarbon resistance and barrier properties that are not possible with untreated HDPE.

Technologies, such as coextrusion and coinjection, allow PET and other plastics to package foods and other products.[225, 226, 227] Care must be taken to control the process so that the melt when blown will not have micro-voids in the container walls or will delaminate. Coextrusion and coinjection (or multilayer processes) are essential technique in the production of high performance BM products (Chapters 4 and 5). The parison or preform is coextruded with a number of different layers, each of which contributes an important property to the finished product. Increasingly, a mid layer may consist of recycled material which is encapsulated between inner and outer layers of virgin plastics.

BMs commonly include from two to seven layers, although more are also used. The construction usually includes one or more barrier layers. These are plastics with a particular resistance to the transmission of water vapor or gases such as oxygen or carbon dioxide. Examples are ethylene vinyl alcohol (EVOH), nylons, and polyvinylidene chloride (PVDC). Their presence greatly enhances the performance of the BM as a package for foodstuffs, beverages, and other critical products. The barrier materials are all deficient in some respect such as price, mechanical strength, and moisture resistance. Thus not used as a material of sole construction for BM. Their use is in thin layers shielded by other more robust and economical body plastics.

Such containers are fabricated by performing conventional extrusion or IBM operations on a multilayer parison or preform. A coextrusion parison head, served by a separate extruder for each distinct component material, is used to produce the parison. The barrier and tie layers are usually very thin, so the flow engineering in the head is critical in order to preserve the integrity of the layers. For this reason, the various melt streams are merged as close to the die exit as possible, even though this complicates die head construction (Figure 6.2). Other disturbing influences, such as parison profiling and intermittent extrusion, are often avoided. If parison profiling is required, the mechanical complication of the parison head is such that axial movement of the die rather than the mandrel usually occurs.

Blow molding process

Blow molding can be divided into three major processing categories (Figure 6.1): extrusion blow molding (EBM) with continuous or intermittent melt producing a parison from an extruder (Chapter 5), injection blow molding (IBM) with noncontinuous melt from an

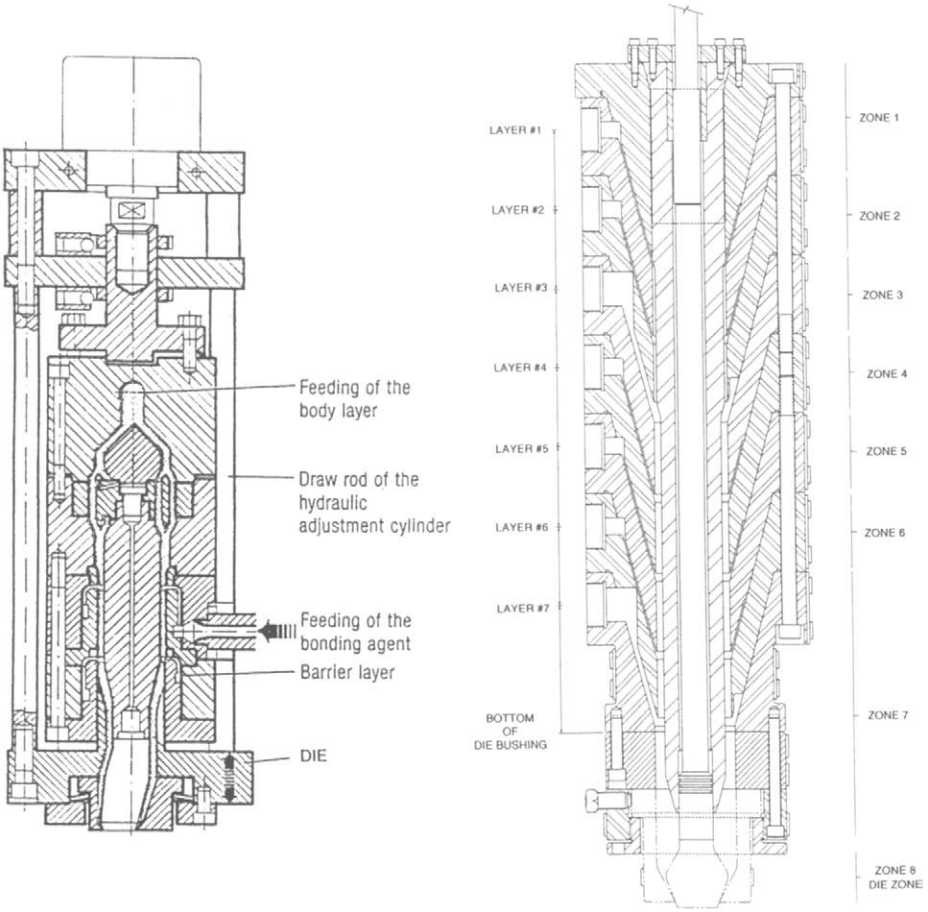

Feeding of the body layer
Draw rod of the hydraulic adjustment cylinder
Feeding of the bonding agent
Barrier layer
DIE
LAYER #1
LAYER #2
LAYER #3
LAYER #4
LAYER #5
LAYER #6
LAYER #7
BOTTOM OF DIE BUSHING
ZONE 1
ZONE 2
ZONE 3
ZONE 4
ZONE 5
ZONE 6
ZONE 7
ZONE 8 DIE ZONE

Figure 6.2 Example of a 3-layer coextrusion parison blow mold head with die profiling (left) and example of a 5-layer coextrusion parison blow mold head with die profiling (courtesy of Graham Machinery Group)

injection molding machine (Chapter 4) that fabricates a preform supported by a metal core pin, and stretched/oriented EBM and IBM to obtain biaxially oriented products providing significantly improved performance-to-cost advantages (Chapters 3 and 5).

Almost 75% of processed plastics are EBM, almost 25% are IBM, and about 1% use other techniques. About 75% of all IBM products are stretched biaxially; there are also stretched EBM. With stretched blow molding orientation takes place simultaneously in the hoop and longitudinal directions. These BM processes offer different advantages in producing different types of products based on the plastics to be used, performance requirements, production quantity, and costs. The parts are formed in a mold that defines the external shape only. As the name implies, the inner shape is defined by fluid pressure, normally compressed air. In this respect, BM differs radically from many molding processes where mold members (male and female cavities are used) determine both inner and outer forms. A major advantage of BM is that the inner form is virtually free of constraints because there is no core to extract. The main drawback is that the inner form is only indirectly defined by the mold, so high precision and independent internal features such as in injection molding are not possible (Chapter 4).

The nature of these processes requires the supply of clean-dry compressed air to blow the hot melt located within the BM female cavity. Other gases can be used, such as carbon dioxide (CO_2), to speed up cooling of the blown melt in the mold. Production can increase usually by at least 20 to 40% by using turbulent chilled air at about -35C (-30F). The gas for blowing usually requires at least a pressure of 30 to 90 psi (0.20 to 0.62 MPa) for EBM and 80 to 145 psi (0.55 to 1 MPa) for IBM. Some of the melts may be exposed as high as 300 psi (2 MPa). Stretch EBM or IBM often requires a pressure up to 580 psi (4 MPa). For IBM of the preform, the pressure is usually 2,000 to 20,000 psi (14 to 138 MPa) and in some cases up to 30,000 psi (207 MPa). The lower blowing pressures generally create lower internal stresses in the solidified plastics and a more proportional stress distribution. The result is improved resistance to all types of stresses (tension, impact, bending, environment, etc.). The higher pressures provide faster molding cycles and ensure excellent conformance to complex shapes.

Pressure to be used depends on plastic being processed. As an example some PE products with heavy walls can be blown and pressed against the mold walls by air pressures as low as 30 to 40 psi. Low pressure can be used since items with heavy walls cool slowly, giving the plastic more time at a lower viscosity to flow into the indentations of the mold surface. Thin walled products cool rapidly: therefore, the plastic reaching the mold surface will have a high melt viscosity and higher pressures (in the range of 50 to 100 psi) will be required. For the larger products, such as 1 gallon bottles, increased air pressure is required (100 to 150 psi). The plastic has to expand further and takes longer to get to the mold surface. During this time the melt temperature will drop somewhat, producing a more viscous plastic mass which requires in it more air pressure to reproduce the details of the mold.

Important that dry air be used. Moisture in the blowing air can cause pockmarks on the inside product surface. This defective appearance is particularly objectionable in thin walled items such as milk bottles. The air performs three functions: it expands the parison or preform against the closed mold cavity, exerts pressure on the expanding plastic to produce surface details on the cavity, and aids in cooling the parison. Various techniques are used to introduce air into the parison with the usual going through the extrusion die mandrel (over which the top of the parison has dropped) or the injection mold core pin that supports the preform. In extrusion BM it can also enter from the pinch-off end of the mold or through the side of the mold, piercing the parison usually using a needle that resembles a hypodermic needle. This side action can be located at the parting line of the mold halves.

The type of molding machine available has an important influence upon the blow opening system used. Some machines, for instance, use needle blowing exclusively. Hollow needle insertion at the mold parting line is considered when a very small opening is required that may even need closing or if the hollow object must be blown up on the side, e.g., on carousels with a series of molds.

During the parison drop between mold halves the air path is used allowing for air to be introduced in the parison as it is being extruded to eliminate collapse of the parison. This allows for certain functions of blowing products where the parison can be closed after it is cut and inflated for certain processes. The target is to develop a high volumetric airflow at a low linear velocity. A high volumetric flow gives the parison a minimum time to cool before coming in contact with the mold and provides a more uniform rate of expansion. A low linear velocity is desirable to prevent a venturi effect from collapsing a portion of the parison while the remainder is expanding. Volumetric flow is controlled by line pressure and orifice diameter. The flow control valves that are located as close as possible to the orifice control linear velocity.

The maximum volumetric flow rate into the cavity at a low linear velocity can be achieved by making the air inlet orifice as large as possible. In the case of blowing inside the neck this is sometimes difficult. Small air orifices may create a venturi effect, producing a partial vacuum in the tube and causing it to collapse. If the linear velocity of the incoming blow air is too high, the force of this air can actually draw the parison away from the extrusion head end of the mold. This results in an unblown parison. Control valves placed as close as possible to the blow tube must carefully regulate air velocity.

With multicavity molds it is usual to employ a crosshead on which the blowing mandrels are arranged in series. Mandrel chains can also be used for product ejection. The channel for the blowing medium should be as large as possible. Angled radial orifices at the tapered end of the mandrel achieve a fast distribution of the cooling media and turbulence.

Extrusion vs. Injection Blow Molding

With EBM, compared to IBM, the advantages include lower tooling costs and incorporation of blown handle-ware, etc. Disadvantages or limitations could be controlling parison swell, producing scrap, limited wall thickness control and plastic distribution, etc. If desired, blown solid handles can be molded during the BM process. Trimming can be accomplished in the mold for certain designed molds, or secondary trimming operations are included in the production lines. With 3-D molding scrap is significantly reduced.

With IBM, a main advantage is that no flash or scrap occurs during processing. It gives the best of all wall thicknesses and plastic distribution control and critical bottleneck finishes are easily molded to a higher accuracy. The initial IBM preforming cavities are designed to have the exact dimensions required after blowing the plastic melt as well as accounting for any shrinkage, etc. that may occur. Neck finishes, internally and externally, can be molded with an accuracy of at least ±4 mil (±0.10 mm). It also offers precise weight control in the finished product accurate to at least ± 0.1 g.

Disadvantages could include its high tooling costs, only solid handle-ware, and it was reported in the past that they were restricted or usually limited to very small products (however large and complex shaped products were fabricated once the market developed). Similar comparisons exist with biaxial orienting EBM or IBM. With respect to coextrusion, the two methods also have similar advantages and disadvantages, but mainly more advantages for both.

When compared to EBM, the IBM procedure permits the use of plastics that are suitable for EBM and, more important, those unsuitable for EBM. Specifically it is those with no controllable melt strength such as the conventional polyethylene terephthalate (PET) that is predominantly used in large quantities using the stretch IBM method for carbonated beverage bottle (liter and other sizes).

Extrusion blow molding

A TP is melted into a tube that is generally referred to as a parison. While still in a heated ductile and firm plastic melt state, the parison is clamped between the cavity halves of a cooled mold, so that the open top and bottom ends of the parison are trapped, compressed and sealed by the mold faces (Chapter 17). Air pressure enters the parison. Air pressure causes the parison to expand like a balloon, so that it takes up

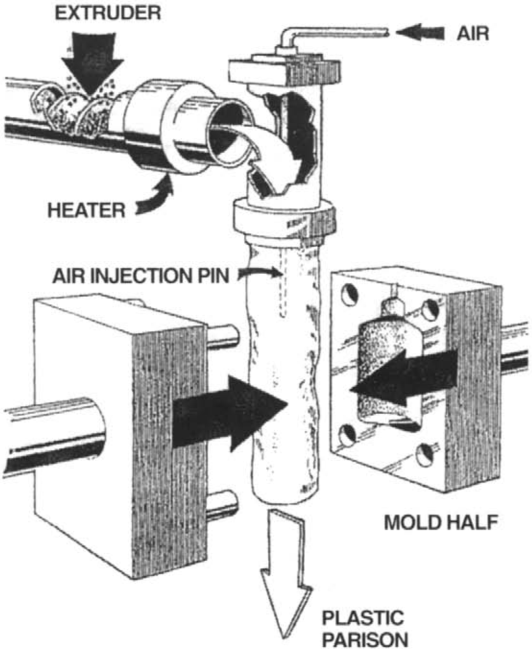


Figure 6.3 Schematic of extrusion blow molding a single parison

the form of the mold cavities (Figure 6.3). Contact with the cooled mold chills the thermoplastic to its solid state.

EBM process starts by preparing a parison that is the plastic melt exiting an extruder (Chapter 5). Understanding and controlling plastic melt flow in the die is important to be successful in BM. Factors directly related to die flow include pressure drop, forces acting on the mandrel, and the distributions of melt velocity around the annular flow gap. Die flow also influences the behavior of the melt after it leaves the die regarding swell. Die design influences the behavior of the parison that is formed at the die lips. As an example if there is a spider to center the mandrel, weld lines will be formed as the melt flows around the legs (Chapter 17). The wall thickness of the BM product can be related to the swelling ratio of the parison (Chapter 17).

Both the quality and cost of a BM container are strongly dependent on the parison swell ratios. If the diameter swell is too small, incomplete handles, tabs, or other unsymmetrical features may result. However if the diameter swell is too large, plastic may be trapped in the mold relief or pleating may occur. Pleating, in turn, can produce webbing in a handle. Weight swell governs the weight, and thus the material cost of the molded product. What is desired is the minimum weight that provides the necessary strength and rigidity.

Because swell is an elastic recoil process that results from molecular orientation in the die, the shape of the die channel has a strong effect on both diameter and thickness swells. The simplest case is a long straight annular die. Here we have only shear flow with no stretching and we would expect to see some orientation in the axial direction. This suggests that there would be no preferential direction of swell and that the diameter swell should be equal to the thickness swell. For the more complex BM dies the swell ratios are strongly influenced by die geometry features, the angle of divergence or convergence of the outer die wall and the variation of gap spacing along the flow path. A diverging die stretches the melt in the hoop direction, and this should reduce diameter swell by counteracting the axial orientation generated by the shear flow (Chapter 17).

Parison sag (drawdown) can cause a large variation in thickness and diameter along the parison, and in an extreme case can cause the parison to break off. For a Newtonian fluid, sag could be kept under control simply by using a material with a sufficiently high viscosity. Plastics being non-Newtonian (Chapter 1) and generally having a melt index of less than one causing sag, sag becomes more severe as the temperature is increased. Since plastic melts are viscoelastic, resistance to sag cannot be quantitatively correlated with viscosity.

The action of pleating (also called draping or curtaining) is a buckling of the parison that occurs when the melt at the top of the parison is unable to withstand the hoop stresses due to the weight of the parison suspended from it. Pleating is undesirable, because it can cause webbing in the blown product. Large diameter swell and a small die gap are factors that will increase the probability of pleating.

Parison Head

The parison head, sometimes called the die head or simply the die, is a specialized form of tube extrusion die (Chapter 17). Its function is to deliver a straight parison in the correct diameter, length, wall thickness, and at the correct temperature for BM. Prior to being clamped in the mold, the parison is suspended unsupported in free air. To avoid undue deformation, it is necessary to extrude the parison vertically downwards.

The BM extruder is almost always arranged in a horizontal attitude, so the first task for the parison head is to turn the melt flow stream through a right angle. This is basically difficult and undesirable but necessary to achieve in a way that meets the essential requirement for a constant flow rate at every point in the annular die gap. A second and related requirement is that the parison should carry as little evidence as possible of the weld line (Chapter 17) formed when the melt stream from the extruder flows around the torpedo even without spiders supporting its core. Many parison die head designs have been evolved to deal with these problems. Examples are shown in Figure 6.4.

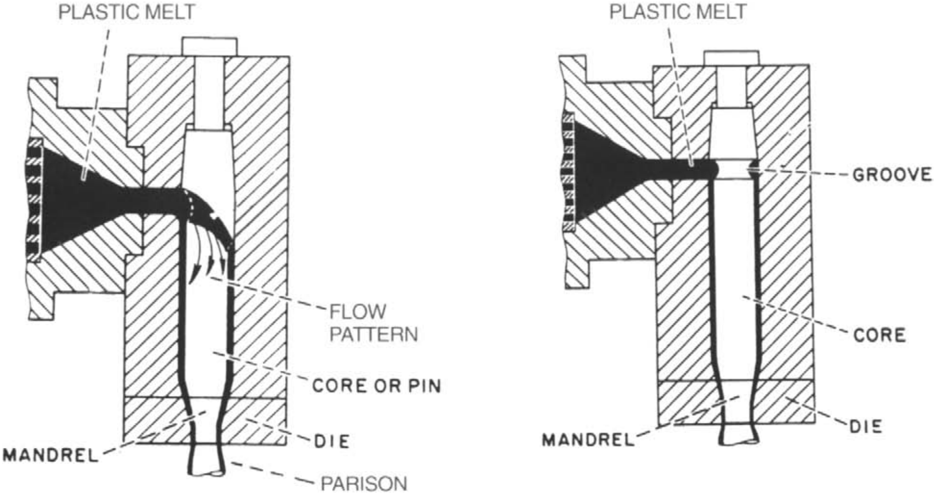


Figure 6.4 Simplified view of a heart shaped parison die head (left) and grooved core parison die head

A potential BM problem is one shared with pipe and tube extrusion dies (Chapter 17). This is the difficulty of ensuring that the mandrel (also called core or torpedo) remain coaxial with the die, without dividing the melt stream with mechanical supports or to much excessive wall thickness deviation. The parison die heads are examples of different design approaches. Those without supports (no spiders) in the melt stream, rely instead on accurate seating between the mandrel and die. The parts need to be relatively massive for this design to be sufficiently rigid. Smaller torpedoes will need supports in the melt stream and here the challenge is to minimize the formation of weld lines in the parison. Such supports include two-spider legs, staggered spider legs, breaker plates, screen tubes, and most useful spiral mandrels. The problem is a difficult one and in the worst case, the weld lines show up as local variations and/or weaknesses in the parison wall thickness.

The ideal parison with a constant wall thickness is not necessarily the optimum for BM. Even simple molded shapes encompass considerable variations in their profile. For example, the body of a bottle is much greater in diameter than the neck. For some containers, there may be several significant variations along the axis, and the effect is usually pronounced in technical BMs. If such articles are BM from a parison of constant wall thickness, then the finished molding will be thinner where the parison has to expand the most and thicker where it has expanded the least. In most cases, the ideal is a finished product with a constant wall thickness at all points. To approach this ideal, what is used is a parison in which the wall thickness varies along the length so that it is thickest where it must expand the most. This is achieved by parison programming or profiling. Usual way to do this is by moving the mandrel in an axial direction relative to the die (Figure 6.5). If both die and mandrel are provided with conical outlet features, this movement will increase or decrease the annular die gap between the two. Servo systems acting on a pre-programmed thickness profile the mandrel movements. The system may include a feedback loop to adjust parison profiling in response to screw speed variations in the extruder.[436]

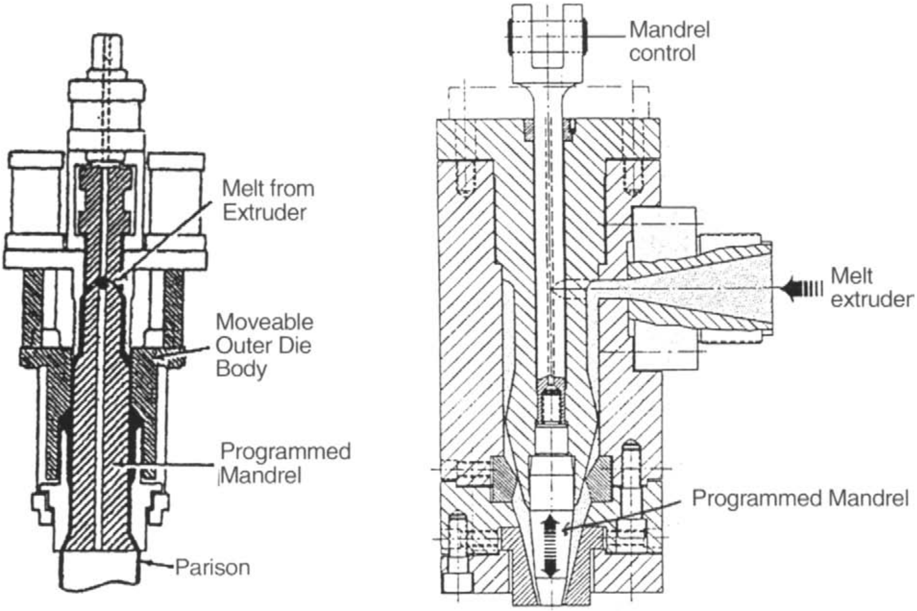


Figure 6.5 Examples of parison wall thickness control by axial movement of the mandrel

There are two types of mandrel and die bushings. One is the convergent type and the other is the divergent type. Selection of which mandrel and die bushing (commonly known in BM as head tooling) is made by the size of the parison necessary. Convergent tooling is the easiest to control and is used whenever possible. Divergent tooling is used when the parison needs to be larger so the tooling causes the parison to flare out as it is extruded. Both convergent and divergent mandrels are mounted directly to the programming mandrel and are programmed up and down to open or close the gap between the pin and bushing. Figure 6.6 is an example for a rectangular shape.

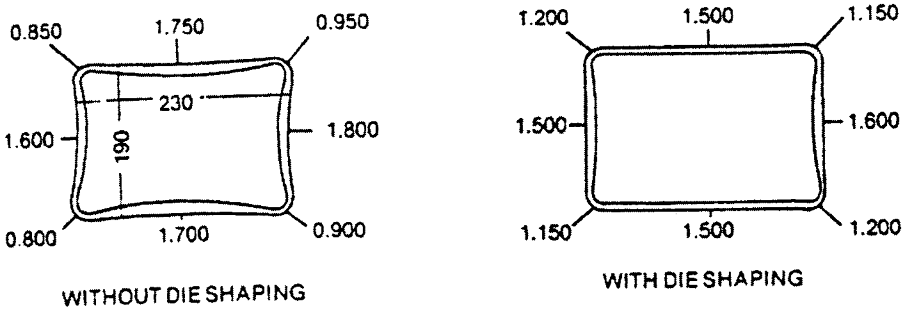


Figure 6.6 Example of rectangular parison shapes where
(1) die opening had a uniform thickness resulting in weak corners and
(2) die opening designed to meet the thickness requirements required

Machine Design

The configuration of individual machines may vary greatly but some essential elements can be distinguished. The extruder and parison head are arranged to extrude a parison vertically between the two halves of a BM. The mold halves are clamped to platens that are linked to a mold closing and clamping device. A blow pin is provided to inject air under pressure into the parison. Because BM is conducted at relatively low pressures, the construction of the machine and mold can be much lighter than is required for injection molding. Consequently, machines, and particularly molds, are lower cost than those used in injection molding. Using multiple molds or multi-cavity molds with multiple parisons can increase machine production rates. These general principles apply to a number of distinct EBM machine (EBMM) designs.

Single-stage EBM produces a blown product in a single integrated process cycle. BM immediately follows parison extrusion and relies on the melt condition of the parison for the deformation and flow necessary to take up the shape of the mold. There is no reheating of the parison before molding. The principal variants are the continuous extrusion and the intermittent extrusion processes. Extrusion in this distinguishing sense applies to extrusion of the parison rather than the operation of the extruder.

Two-stage EBM treats the parison as a true preform by separating the functions of parison preparation and BM. Parisons are produced by conventional tube extrusion methods (Chapter 5). The tube is cooled and cut into parison lengths that are stored before being reheated and BM in the normal way.

In the continuous extrusion design process, the parison is continuously extruded between the open mold halves from an accumulator head. When the required length of parison has been produced, the mold is closed, trapping the parison that is severed usually by a hot knife from the die. Figure 6.7 provides a simplified schematic of a continuous BM process. Land or pinch-off areas on the mold compress and seal the upper and lower ends of the parison to make an elastic airtight part. Compressed air is introduced through the blow pin into the interior of the sealed parison that expands to take up the shape of the mold cavities. The cooled mold chills the blown object that can then be ejected when the mold opens.

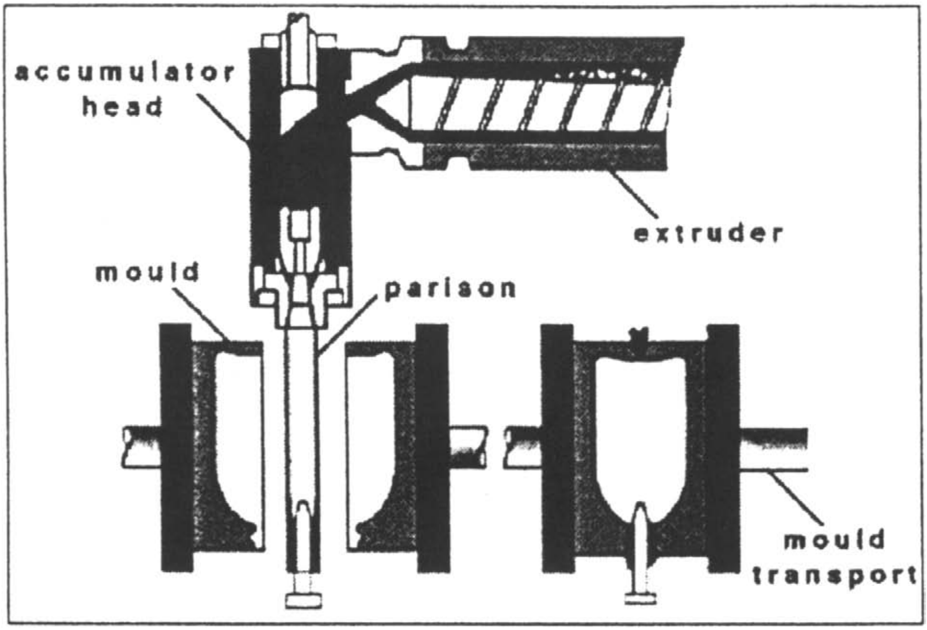


Figure 6.7 Introduction to a continuous extruded blow molding system with its accumulator die head

Two or more molds can be used in a shuttle arrangement, so that one or one set is open for parison extrusion while the others are performing the blowing and cooling cycle. There is also a method of mold rotary movement that results in very high production rates. In such machines, known as horizontal or vertical wheel machines (also called carousel or ferris wheel machines) a number of molds are mounted on a rotary table (Figure 7.8). Movement of the table carries the closed mold away and presents a new open mold to the diehead, so allowing extrusion to continue.

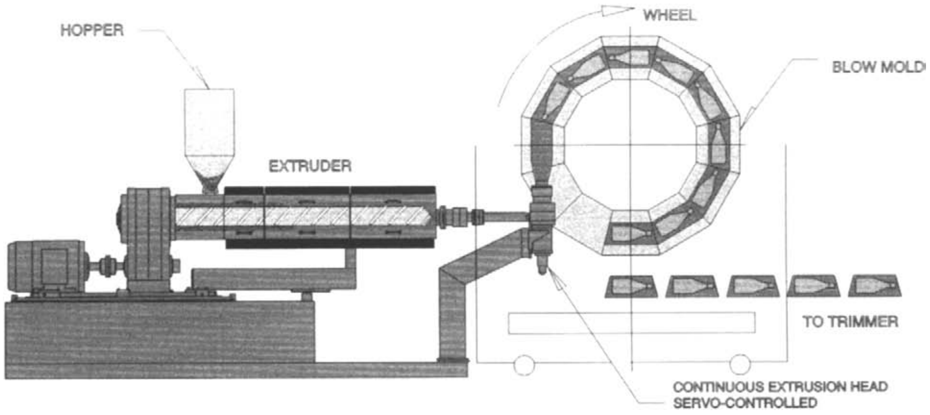


Figure 6.8 Schematics of vertical wheel machine in a production line (courtesy of Graham Machinery Group)

Intermittent accumulator EBM machines use a normal conventional axially fixed continuously operating extruder to prepare the melt. The accumulator is a heated reservoir where the melt is temporarily stored in the intervals between parison extrusion (similar action of a two-stage injection molding machine (IMM) as reviewed in Chapter 4. Also used is a conventional reciprocating IMM that delivers melt through a die into a blow mold.

Injection blow molding

The injection blow molding (IBM) process uses an injection molding machine rather than extruder to produce the precursor (Chapter 4). This precursor is called a preform rather than a parison as in EBM. A major advantage in IBM vs. EBM is that the preform shape can be designed to obtain a more uniform or desired wall thickness when BM. The process consists of blowing a molten thermoplastic against the inside walls of a female mold cavity and chilling it to a rigid solid product. The IBM machine (IBMM) has an integral injection unit and a multi-impression mold assembly in which the mold cores are usually mounted on a rotary table. The cores double as blowing pins and index in the basic 120° steps between the basics of injection, blowing, and ejection stations (Figure 6.9).

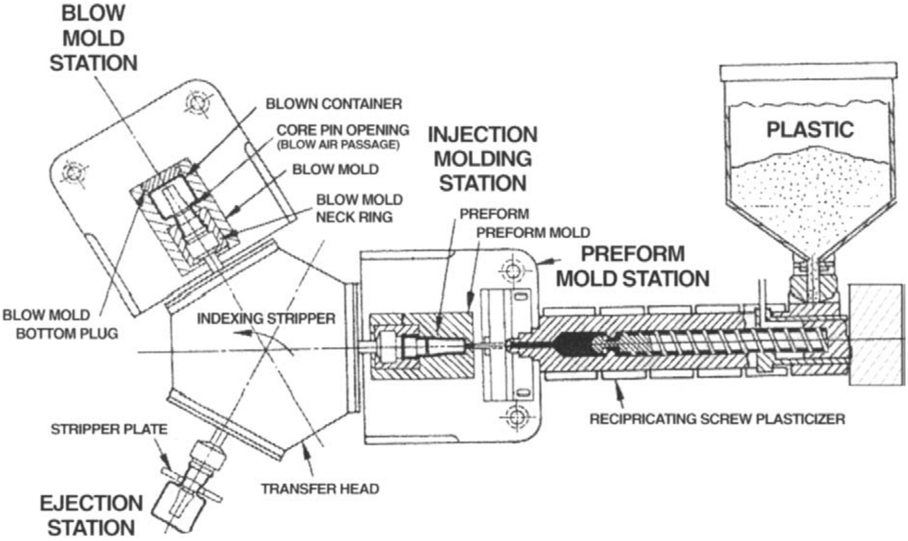

BLOW MOLD STATION
BLOWN CONTAINER
CORE PIN OPENING (BLOW AIR PASSAGE)
BLOW MOLD
BLOW MOLD NECK RING
INJECTION MOLDING STATION
PLASTIC
PREFORM
PREFORM MOLD
PREFORM MOLD STATION
BLOW MOLD BOTTOM PLUG
INDEXING STRIPPER
RECIPRICATING SCREW PLASTICIZER
STRIPPER PLATE
TRANSFER HEAD
EJECTION STATION

Figure 6.9 Three station injection blow molding system

First station usually has multiple preform injection molds where preforms are formed over core pins. The preforms have hemispherical closed ends (resembles a laboratory test tube). The other ends have an open bore, formed by the core pin. External details, such as the thread and neck flange for a screw-top container, are directly produced by injection molding. While the preform is still hot, the injection split mold is opened and the preforms, still on the core pins, are rotated to the blowing station two. Here the preforms are enclosed within the blow mold, and introducing blowing air through the core pins followed with cooling produces the BM. Blow molds opened and the finished products, still on the core pins, are rotated to an ejection station where they are stripped off mechanically and/or air.

In addition to the 3-station IBM machines there are those that have more stations with the usual being a 4-station machine. The extra station(s) can provide extra heat/cooling cycles, tighter dimensions, in-mold labeling, etc. Conventional IMMs with applicable molds have been used to BM containers (Chapter 4). After the machine prepares the preforms on the cores, the mold opens and is shuttled (upward, sideway, or other position) to blowing station. After containers are ejected from their pins, the mold shuttles back between the machine platens to repeat the cycle.

Integral hollow handles to date are not practical, however solid integral handles can be included during fabrication. Examples of solid handles are shown in Figure 6.10. A patent was issued during 1913 that produced an integral solid handle during unstretched (or stretched) IBM of a bottle. French patent No. 1,192,475 was issued to the Italian company Manifattura Ceramica Pozzi SpA.

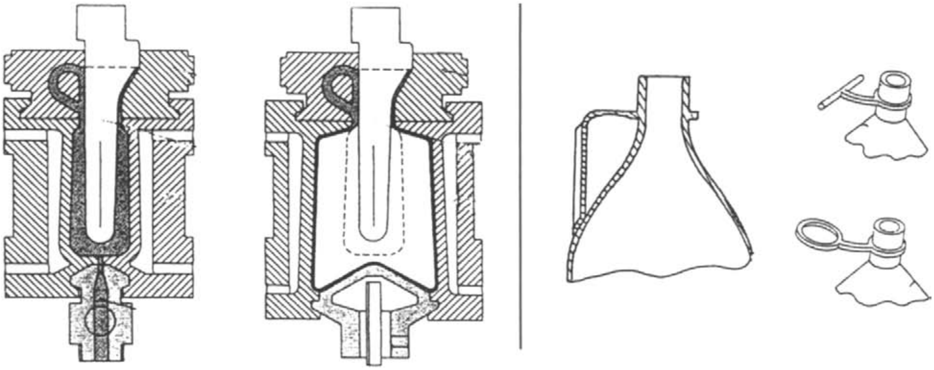


Figure 6.10 Schematic of injection blow mold with a solid handle (left) and simple handles (ring, strap, etc.) can be molded with blow molded bottles

STRETCH BLOW MOLDING

Stretch blow molding (SBM) may be performed by the injection or extrusion processes.[222] Stretching during BM produces biaxial orientation in the blown article (Chapters 3 and 5). Conventional BM imparts a degree of circumferential orientation, caused by the expansion of the parison into the mold cavity, but there is little or no axial expansion and correspondingly, no axial orientation. SBM provides for axial orientation by stretching the preform or parison axially before or during blowing. This is normally accomplished by means of a stretch rod that is advanced axially inside the preform or parison at a controlled rate. Another axial stretching system literally clamps the ends and stretches them apart. When compared to non-stretch BM, SBM technology provides significant advantages performancewise and costwise.

The oriented stretch blow type are characterized by factors that include increased strength and rigidity, increased resistance to burst pressure, better transparency and gloss, and reduced permeability. The improved strength can result in savings on additives such as impact modifiers. Specially developed nucleated or clarified random copolymer grades produce a blown bottle of glass-like transparency. Very significant is that they can be made lighter and cheaper offsetting the higher capital cost of equipment. The lighter weight stretched container results in reduced handling, transport, and warehousing costs. Stretch blow processes can produce containers with solid integral handles (Figure 6.10).

In the injection stretch blow molding (ISBM) process the neck profile complete with screw thread is entirely formed by injection molding and is generally not modified by the blowing process. The other end of the preform is closed and typically dome shaped. The design and precision of the preform has a critical influence on the degree of orientation and quality of the blown article. Popular worldwide for producing IBM are polyethylene terephthalate (PET) carbonated drink bottles and also other plastics such as PVC.[223, 224] The IM preform may be converted to a BM either by the single-stage or the two-stage process.

Not all thermoplastics can be oriented. The major thermoplastics used are polyethylene terephthalate (PET), polyacrylonitrile (PAN), polyvinyl chloride (PVC), and polypropylene (PP). PET is by far the largest volume material, followed by PVC, PP, and PAN. The amorphous materials, e.g., PET, with a wide range of thermoplasticity are easier to stretch blow than the partially crystalline types such as PP (Chapter 1). In the single-stage (or one-step) injection stretch BM process, the preform injection molding step is integrated with the stretch blow machinery. The machines are generally arranged for rotary operation, so that the preforms pass directly from the injection molding station to a thermal conditioning station and thence to a stretch BM station.

Once the parison is formed (either injection or extruded), it passes through conditioning stations which bring it to the proper orientation profile temperature from end to end. The single-stage system allows the process to proceed from raw material to finished product in one machine. The thermal conditioning process is the most critical part of this process. The optimum stretch blow temperature span can be very narrow ranging from within about 10C. Uniform heating of the order of ±1C is important. Thermal conditioning stations include up to 36 independently controlled heat zones, typically using a combination of infrared radiant external heaters and hot air for internal heating.

The thermally conditioned preform is transferred to a blow mold and stretched and oriented axially by an internal stretch rod or mechanical grip stretching, either immediately prior to, or simultaneously with the blowing operation that provides radial stretch and orientation (Figure 6.11). Blowing pressures range up to about 40 bar. The blow mold temperature is relatively high at 35 to 65C in order to minimize strain in the bottle. For a given bottle size, the degree of orientation is determined principally by the parison length and diameter. Stretch ratios are relatively high. In the wall thickness of the bottle body, the amount may be as high as 15:1. Axial stretch is about 4:1; diametrical stretch ranges about 3.5:1

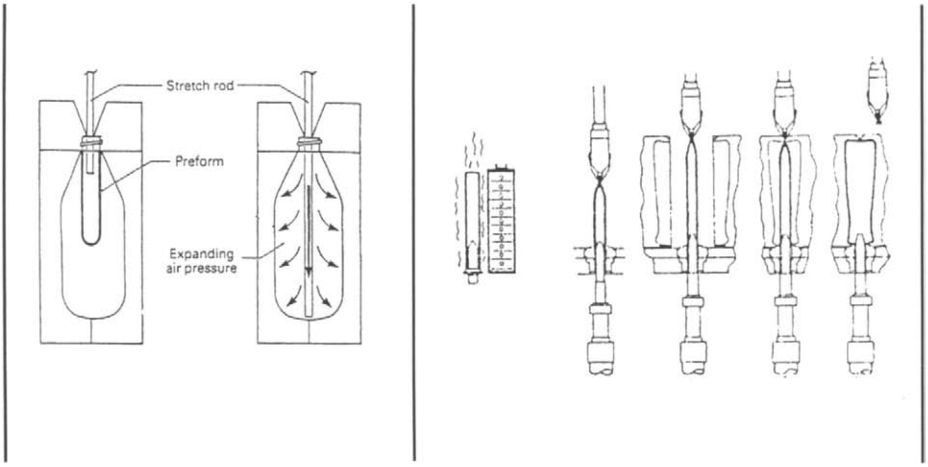


Figure 6.11 Example of stretched injection blow molding using a rod (left) and example of stretched injection blow molding by gripping and stretching the preform

With the two-stage process, processing parameters for both preform manufacturing and bottle blowing can be optimized. A processor does not have to make compromises for preform design and weight, production rates, and bottle quality as done on single-stage equipment. One can either make or buy preforms. And if one chooses to make them, one can do so in one or more locations suitable to the market. Both high-output machines and low out-put machines are available. The two-stage process, which permits injection molding of the preform and then shipping to BM locations, has allowed companies to become preform producers and to sell to BM producers. Thus companies that wish to enter the market with oriented containers can minimize their capital requirements.

Extrusion stretch blow molding (ESBM) is a one-stage or two-stage process using two mold/mandrel sets where one is for preblow and the other for final blow. An extruded parison is first pinched off and blown conventionally in a relatively small preblow mold to produce a closed-end preform. The preform is then transferred to the final blow mold where usually an extending stretch rod within the blowing mandrel bears on the closed preform end to stretch it axially. The stretched preform is then blown to impart circumferential stretch. Standard BM machines can be converted for extrusion stretch BM. The process is most often used for PVC bottles.

Oriented PVC containers most commonly are made on single-stage, extrusion-type machines. The parison is extruded on either single- or double-head units. Temperature conditioning, stretching, and thread forming are done in a variety of ways depending on the design of the machine. Many of the processes in use are proprietary.

Dip Blow Molding

The dip BM process bears some resemblance to IBM in that it is a single-stage process performed with a preform on a core/blow pin.The difference is in the way the preform is made. The process uses an accumulator cylinder that is fed by an extruder. The cylinder has an injection ram at one end while the other is a free fit over the blow pin. The blow pin is dipped into the melt so that a neck mold on the pin seals the end of the accumulator cylinder. The injection ram is advanced to fill the neck mold; then the blow pin is withdrawn at a controlled rate so that it is coated with a melt layer extruded through the annular gap between the pin and the accumulator cylinder. The thickness of the coating can be varied or profiled to an extent by varying the speed of the blow pin and the pressure on the injection ram. After trimming, the preform is BM in the same manner used for IBM.

The process results in a seam and flash free container with a high quality molded neck. The preform is produced at a lower pressure than that used for injection molding, so the machine can be lighter and of lower cost constructed. The preform is formed under relatively low stress. Process is best suited to the production of smaller containers.

Multiblow Blow Molding

The process is used for high volume BM of very small containers such as pharmaceutical vials and whiskey bottles. A multi-cavity mold is used with an extruded parison whose circumference approaches twice the total width of the closely spaced cavities. Before the mold closes, the parison is stretched and semi-flattened laterally so that it extends across the full width of the cavities. The process is usually combined with blow/fill/seal techniques.

Sequential Extrusion

Sequential EBM is a special multi-material technique used for the production of special designed products. The different plastics are chosen typically to contribute complementary mechanical properties and are present in distinct sequential zones in the finished part. Normally two materials are used but three or more are also used. Separate external ram accumulators for each material serve the die head. These are operated sequentially, typically in A-B-A sequence, to produce a parison with three distinct material zones in axial succession. The parison is subsequently BM by normal techniques.

An example for sequentially BM polypropylene is an automotive air duct in which a central flexible zone (Figure 6.12) joins rigid end sections. The flexible zone allows for installation mismatches, accommodates thermal expansion, and damps vibration noise. The rigid portions allow for direct connection to other mechanical elements in the assembly.

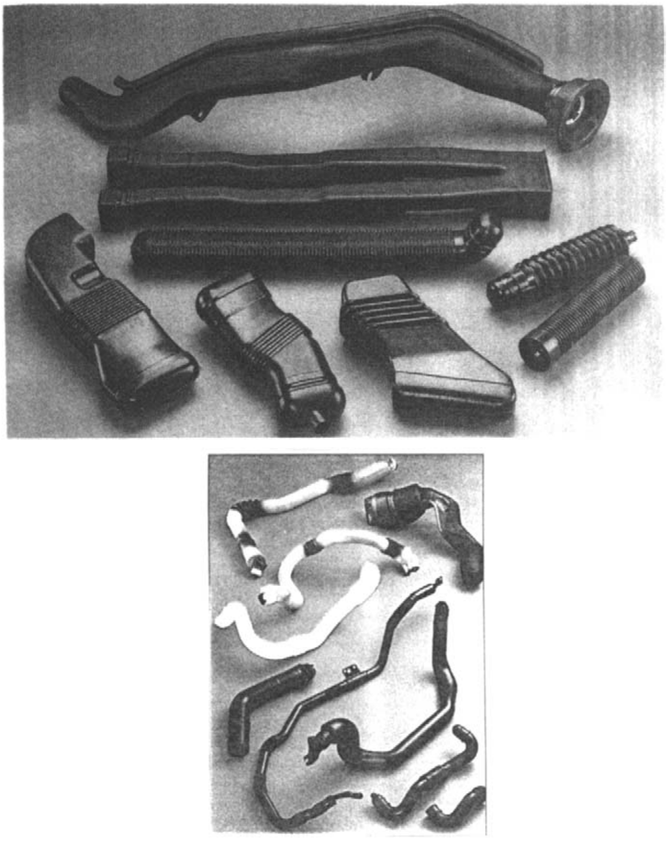


Figure 6.12 Examples of different shaped sequential extrusion blow molding products

Blow/Fill/Seal

The blow/fill/seal process is a complete packaging technique that integrates the extrusion or IBM and container filling steps. This can provide for aseptic filling of the hot as-blown container and is used for pharmaceutical, food, and cosmetic products. The process employs a two-part mold in which the container body mold cavity blocks are separate from the neck-forming members.

The body mold closes on the parison that is blown normally by a neck calibrating blow pin. Immediately, with the mold still closed, the liquid contents are injected through the pin. The pin is then withdrawn and the neck is formed and sealed under vacuum by the neck-forming members. Both mold parts then open to eject a filled and sealed container. Small containers may be formed entirely by vacuum rather than blowing.

Blow Molding 3-D

Because EBM is performed on a cylindrical parison, the conventional process is not well suited to the production of products with complex forms that deviate substantially from the parison axis. Such forms can be produced by conventional BM equipment, but only by using a parison that in its form blankets the complex mold cavity. This 3-D process in the past usually developed an excessive amount of pinch-off scrap. During the past few decades developments in parison handling robot equipment and in blow mold design make it possible to manipulate a relatively small parison into the complex mold cavity. The result is a BM largely free of flash and scrap and offering considerable process savings. There are many such techniques, some of them proprietary property, and they are collectively known as 3-D blow molding. Examples are shown in Figures 6.13 and 6.14.

Blow Molding with Rotation

The injection molding with rotation (MWR) is an example of processing at lower temperatures, pressure, etc. It is also called injection spin molding or injection stretched molding. This BM process combines injection molding and IBM, as performed in IBM reviewed, except it has the additional step of with melt orientation (Dow patent). The equipment used is what is commercially available for IM except the mold is modified so that either the core pin or outside cavity rotates. The rotated melt on its preform pin is transferred to a blow mold. The end product can come directly from the IMM mold or be a result of two-stage fabrication: making a parison and BM the parison.[164]

This technology is most effective when employed with articles having a polar axis of symmetry; having reasonably uniform wall thickness; and

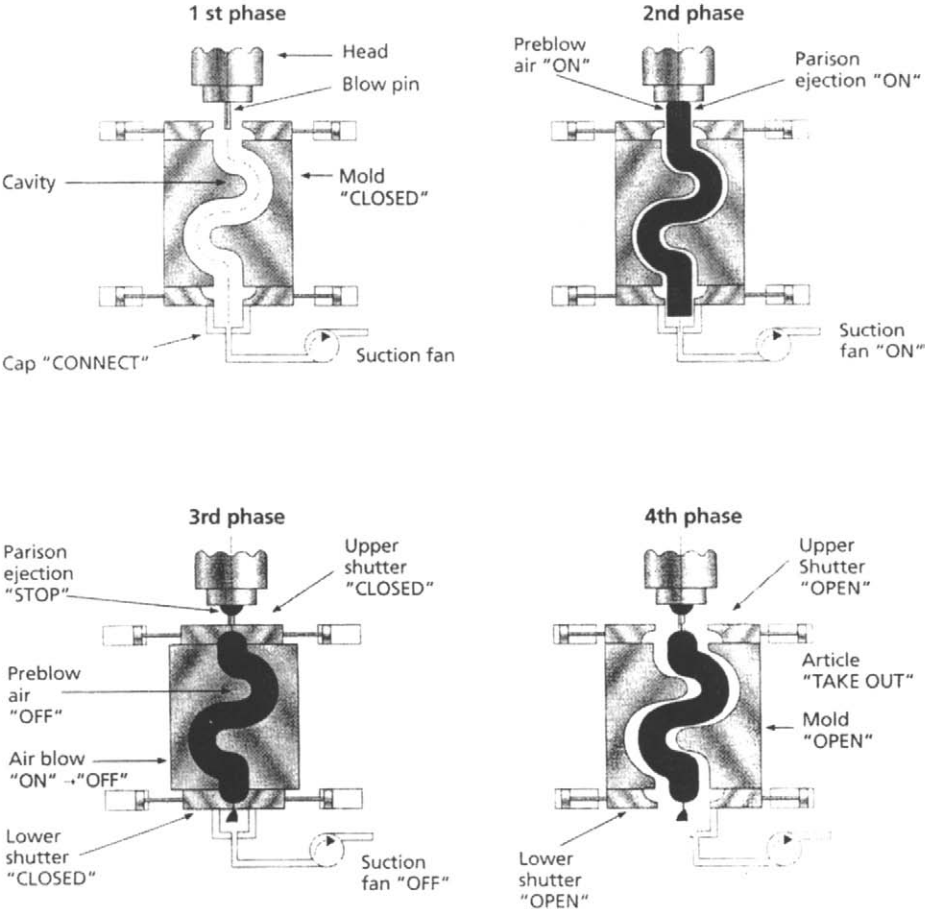

1 st phase
Head
Blow pin
Cavity
Mold "CLOSED"
Cap "CONNECT"
Suction fan
2nd phase
Preblow air "ON"
Parison ejection "ON"
Suction fan "ON"
3rd phase
Parison ejection "STOP"
Upper shutter "CLOSED"
Preblow air "OFF"
Air blow "ON" → "OFF"
Lower shutter "CLOSED"
Suction fan "OFF"
4th phase
Upper Shutter "OPEN"
Article "TAKE OUT"
Mold "OPEN"
Lower shutter "OPEN"

Figure 6.13 Example of a suction extrusion blow molding process fabricating 3-D products (courtesy of SIG Plastics International)

whose dimensional specifications and part-to-part trueness are important to market acceptance. The MWR process requires no sacrifice of either cycle time or surface finish. Both laboratory and early (past) commercial runs identify good potentials for reducing cycle time; for either reducing the amount of plastic required or improving properties with the same amount of plastic, or both; and for substituting less expensive plastics while achieving adequate properties in the fabricated product.

During fabrication using the MWR process, two forces act on the plastic: injection (longitudinal) and rotation (hoop). The targeted balanced orientation is a result of those forces. As the product wall cools, additional high-magnitude, cross-laminated orientation is developed frozen in and throughout the wall thickness. Orientation on molecular

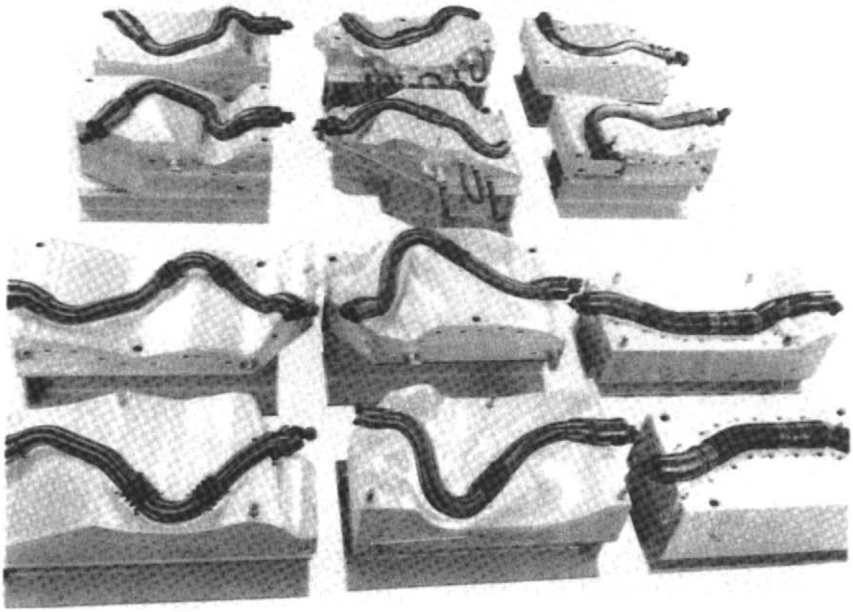


Figure 6.14 Examples of 3-D extrusion blow molded products in their mold cavities (courtesy of SIG Plastics International)

planes occurs as each layer cools after injection. This orientation can change direction and magnitude as a function of wall thickness. The result is analogous to plywood or reinforced plastics (Chapter 15) and the strength improvements are as dramatic. In the MWR process, there is an infinite number of microscopic layers each of which has its own controlled direction of orientation. By appropriate processing conditions, both the magnitude and direction of the orientation and strength properties can be varied and controlled throughout the wall thickness.

MOLD

Blow mold usually consists of two halves, each containing cavities which, when the mold is closed, define the exterior shape of the BM (Chapter 17). Multiple cavity molds are used. Because the process produces a hollow article, there are no cores to define the inner shape. Mold details and actions will vary considerably according to the geometry of the product and the BM process in use. Even though the following review concentrates on EBM, the information can also be applied to IBM. The two halves that meet on a plane are known as the parting line. The plane is chosen so that neither cavity half presents an undercut in the direction of mold opening. For most bottle designs, this requirement presents little or no difficulty.

For products of asymmetrical cross-section, the parting line is placed in the direction of the greater dimension (Figure 6.15). Guide pillars/pins and bushings to ensure that there is no mismatch between the cavities align the two mold halves. With EBM the parison passes across the mold in the axis of the cavity and is pinched and compressed between the faces of the closing mold at the neck and base regions of the cavity. These are known as the pinch-off zones. Separate inserted mold blocks typically form the base and neck regions of the mold. The mold includes channels for the circulation of cooling water.

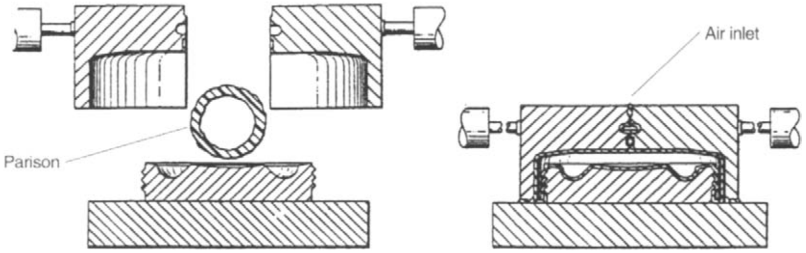


Figure 6.15 Example of a 3-part mold to fabricate a complex threaded lid

With injection BM the preform only has a pinch-off at the neck. In EBM the pinch-off zone performs two functions. It must weld the parison to make a closed vessel that will contain blowing air, and it must leave pinched-off waste material in a condition to be removed easily from the blown product.[164]

Flash caused by the pinch-off is an unavoidable evil in EBM. Ability to control the adverse effects of the flash is critical to success of the process.[228] Pinch-off generates excess material in the form of flash that is usually twice the thickness of the parts wall. This thicker plastic cools slower than the blown product. It is subject to fold-over and can adhere to the blown product. Flash imposes costly limits on BM efficiency. It has potential for significantly extending the molding cycle, primarily by increasing the time needed to cool the thick flash. This cycle increase could approach twice what would normally be required. Removal calls for a post-molding trim step that requires secondary equipment and poses a risk of damaging good parts.

To reduce the time cycle a fabricator has some damaging options such as ejecting the part before the flash is sufficiently cooled. Because it is still soft and pliable when ejected, it can create other problems such as a fold over on itself and adhering to adjoining surfaces of the part after ejection of the molding. Flash is also considerably more difficult to handle and trim while hot. In either case, the resultant penalty may be a significant increase in the part reject rate. By locating cooling lines as close as possible to the flash heat transfer to the cooling water will reduce cycle time. So it is critical to appreciate maximizing the heat transfer as much as possible to the flash area. By keeping the water turbulent takes advantage of operating the water in the proper Reynold's number (Chapter 17).

When a parison is blown, a large volume of air must be displaced from the mold cavity in a short time. Because blowing is carried out at relatively low pressure, it is essential to provide venting to allow this air to escape without resistance. Unless a gloss finish is required on the molding, it is common practice to sandblast the cavity to a fine matt finish. This helps air to escape as the expanding parison touches the cavity face but it is not sufficient in itself. Vent slots may be cut at appropriate points into the mold parting face to a depth of 0.05 to 0.15 mm. The appropriate point is where there is a possibility for air to collect as the hot plastic expands in the cavity.

Venting can also be provided within the mold cavity by means of inserts equiped with vent slots, porous sintered plugs, or by holes with a diameter not greater than 0.2 mm. Such holes are machined only to a shallow depth and are relieved by a much larger bore machined from the back of the mold.

Efficient mold cooling is essential for economical BM. As in injection molding typically, up to 80% of a BM cycle is devoted to cooling. Molds are constructed as far as possible from high thermal conductivity aluminum alloys, and water cooling channels are placed as close as possible to the surface of cavities and pinch-off zones. Because BM is a relatively low pressure process, the channels can be quite close to the surface and quite closely spaced before mold strength is compromised. The actual dimensions will depend on the heat transfer rate and cooling temperature requirements for the material of construction and plastic being processed. As a guide, channels may approach within 10 mm of the cavity and center spacing should not be less than twice the channel diameter. If the mold body is cast, the cooling channels can be fabricated in copper pipe to closely follow the cavity contours before being cast in place. If the mold is machined, drilling and milling will produce channels, and it is not usually possible to follow the cavity contours so closely (Chapter 17).

An alternative in cast molds is a large flood chamber (Figure 6.16). However, efficient water cooling requires turbulent flow and this may not be attained in a flood chamber or in large coolant channels (Chapter 17). Many small channels are better than a few large ones. The cooling circuits will normally be zoned so that different areas of the mold can be independently controlled. The coolant flow rate should be sufficient to ensure turbulent flow and to keep the temperature differential between inlet and outlet to about 3C.

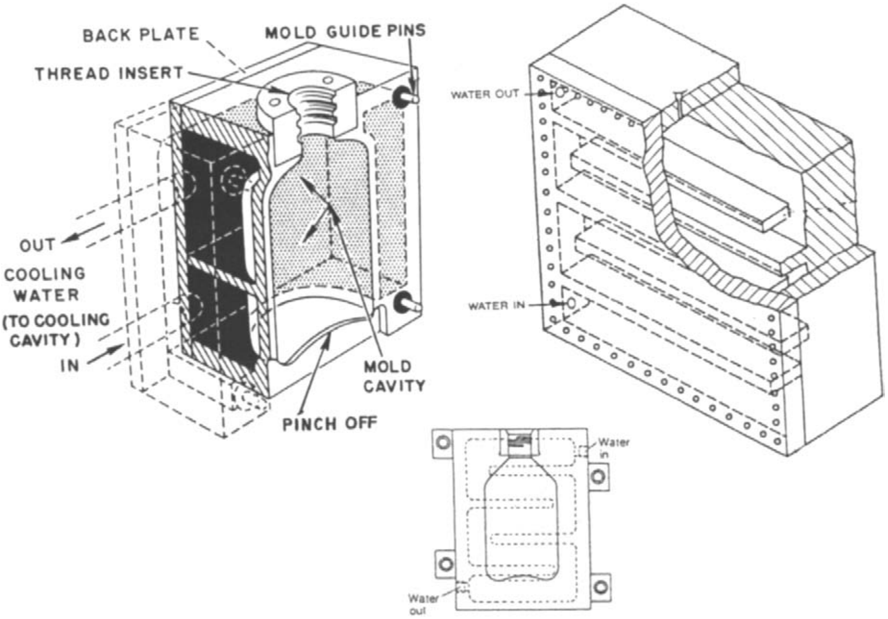

BACK PLATE
MOLD GUIDE PINS
THREAD INSERT
OUT
COOLING WATER (TO COOLING CAVITY)
IN
MOLD CAVITY
PINCH OFF
WATER OUT
WATER IN
Water in
Water out

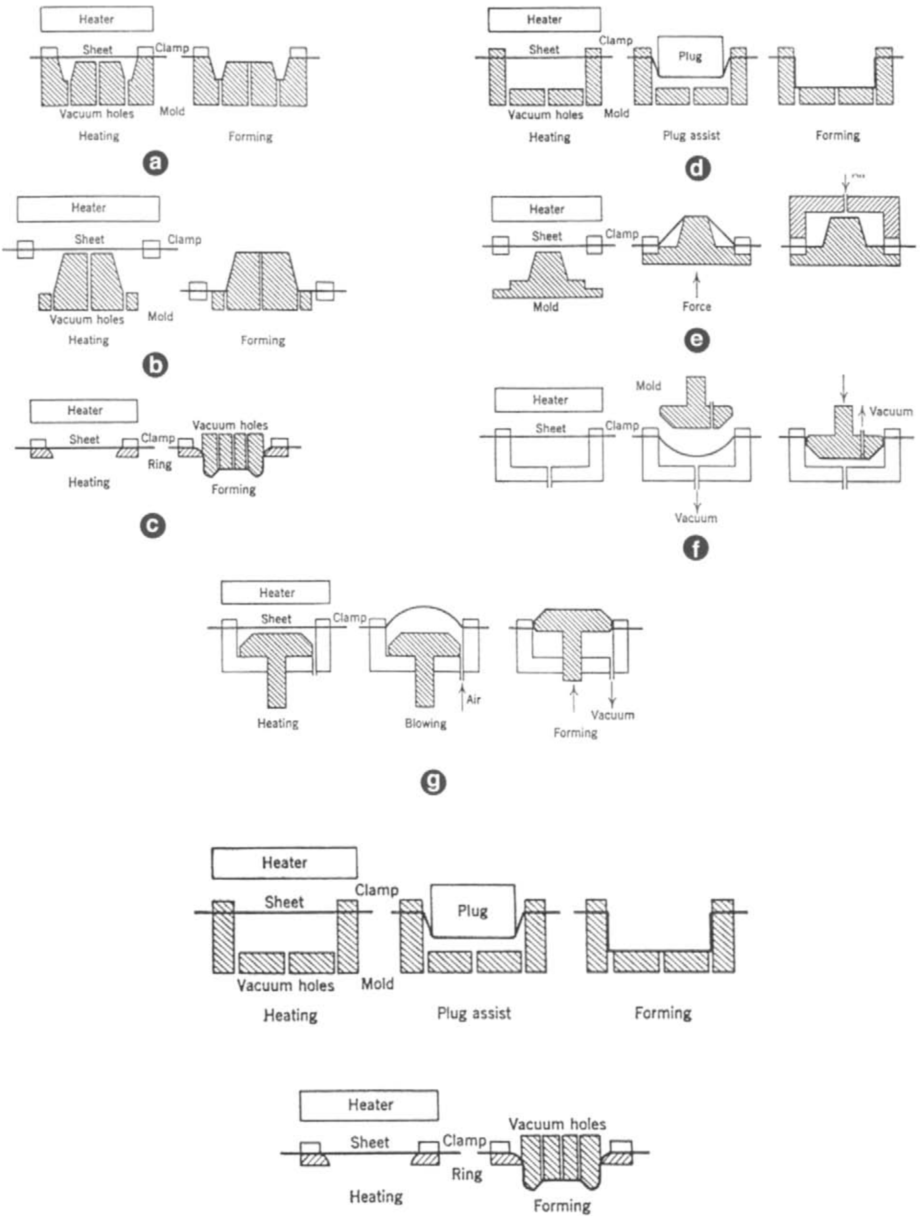
Figure 6.16 Examples of water flood cooling blow molding molds

7 THERMOFORMING

Introduction

Thermoforming is a process for converting thermoplastics into shell forms, using plastic sheet or film as a preform. Processes permit forming many small to large durable varied shapes. The various forming techniques permit manufacture of products individually or on mass production-continuous belt type production that are used in many different markets. Products include machinery and tool housings, industrial pallets, boat hulls, computer housings, transportation [auto, bus, aircraft, etc.] components, refrigerator door liners, etc. Typical products are high production items such as plates, cups, lids, trays, containers, etc. Many different methods of thermoforming are used. Figure 7.1 provides an introduction to the thermoforming methods.

With the exception of a few such as matched mold, hybrid billet [combines thermoforming and blow molding,[245] and twin sheet thermoforming, the forming process uses an open mold that defines only one surface of the thermoformed part. The second surface is only indirectly defined by the mold. This second surface will lack precision definition of features to an extent dependent partly on the sheet thickness and thickness tolerance as well as the uniformity in heat subjected to the sheet prior to forming.[1, 28, 194, 229, 230, 231, 232–237, 476] There is no direct control over wall thickness of the formed part; this will vary from feature to feature according to the degree of stretch and thinning experienced at that point. Normally, it will be a target in thermoforming to obtain as even a wall thickness as possible in the finished part. Because the basic process uses a sheet preform and a single-surface mold, it is not possible to create independent features on the second surface. These processing considerations confine most thermoformed parts to relatively simple shapes however there are different complex 3-D parts formed.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Vacuum holes
Heating
Forming

Figure 7.1 Examples of thermoforming methods

Identification of thermoforming is related to the thickness of the plastic processed. There are thin-gauge and thick-gauge or heavy-gauge thermoforming processes. Thin-gauge identifies sheet thickness that is less than 0.06 in. (0.15 cm). Film forming is a form of thin-gauge forming where the plastic thickness is less than about 0.01 in. (0.025 cm).

Heavy-gauge means that the sheet thickness is greater than about 0.1 in. (0.25 cm). There is also plate forming or heavy-gauge forming where the sheet thickness is greater than about 0.4 in. (1 cm). Although polystyrene and polyolefin foam sheet thicknesses can exceed 0.01 in. (0.25 cm), these foams are usually treated as thin-gauge sheet stock. This classification is also used to further classify forming by machinery type, product type, and processing problems.

To form thermoplastic sheets or films they must be heated to the drawing temperature just prior to and during the drawing cycle that uses a forming force. The plastic can be heated in an oven, heated tunnel, on a mold plate, or preheated on a hot plate. Plastic is heated only a few degrees above its glass transition temperature (T_g) or melt temperature (T_m) (Chapter 1). Combinations of preheating with mold heating have advantages particularly in production runs. Target in heating plastic material to be thermoformed is to heat rapidly with a minimum temperature gradient from its edge to center and throughout the sheet thickness. The material when formed in the mold or die is held in position by some mechanical device such as clamps or pressurized hold-down plates. During forming the heated flexible/rubbery sheet is stretched against a rigid surface mold cavity. Vacuum (causes atmospheric air pressure), positive – dry air pressure, or power press can supply forming force. Power press supplies forming force in matched mold forming and so, in principle, is almost unlimited performing in compression molding (Chapter 14). In practice, the force is limited by the design of mold construction as well as the needs of the process and is usually in the range 1.5 MPa to 4 MPa (218 psi to 580 psi).

After being drawn the sheet material must be cooled to harden. Frequently chill boxes, cold plates, and/or cool air systems are included in the forming mold equipment. In practice thermoforming processes all have two or three optional forms. These options can be assembled in many different permutations to create a very wide variety of thermoforming processes. Plastics forming capabilities relate to their pressure stretch and draw ratio that identifies depth to draw ratio. It is the ratio of the surface of the formed part to the net starting area of the original sheet. As an introduction to this subject with an appropriate plastic an average stretch ratio is 3 to 1 for pneumatic forming. The draw ratio is the maximum depth of the forming mold to the minimum distance across the open face at any given location on the mold; the usual draw ratio is 1 to 1.

The linear draw ratio is where the ratio of the length of a scribed line on the formed product is compared to that of the scribed line on the unformed sheet used to form the product. It is a measure of the overall uniaxial elongation the plastic must have at the forming opening. It can be defined only for simple, symmetrical shapes in respect to an axis. This temperature-dependent draw ratio is used primarily to screen candidate plastics and to help define potential forming processing windows.

Some plastic sheets stretch as much as 600%, others as little as 15%. This behavior directly influences what shapes can be formed and their quality. Those with a putty-like appearance respond to very small pressures; others, which tend to be stiff, require heavier operating equipment. The pressure response is somewhat related to the ability to be stretched while hot.

The temperature used to form sheets varies with material type, thickness, size, and depth of draw. Other important factors include process to be used and speed of operation. The most efficient temperature for a specific product is generally determined by a combination of drawing temperature previously experienced and/or experimenting. Too high a temperature may cause sags, heat-marks, or tearing. With too low a temperature wrinkles and cuts/fracture can occur. The most useful formable plastics do not have sharp melting points. Their softening with increasing heat is gradual. Each material has its own range of heat, wide or narrow, within which it can be effectively formed. This single property is one of the most important of all the factors involved in forming.

When the plastic is forced into contact with the mold at pressures greater than atmospheric, air is trapped between the plastic and mold. Venting is provided by simple passages connecting to the atmosphere but is often improved by using a vacuum on the mold side of the sheet. In this case, the venting vacuum increases the forming force by an increment approaching one atmosphere.

Industrial clean compressed air supply systems normally operate at about 550 kPa to 710 kPa (80 psi to 100 psi) and this pressure may be sufficient for many forming applications. Certain pressure forming equipment operate at pressures up to about 2500 kPa (360 psi), with some processes operating up to at least 4 MPa (580 psi). These pressures are very low when compared to those commonly used for injection molding or extrusion (Chapters 4 and 5).

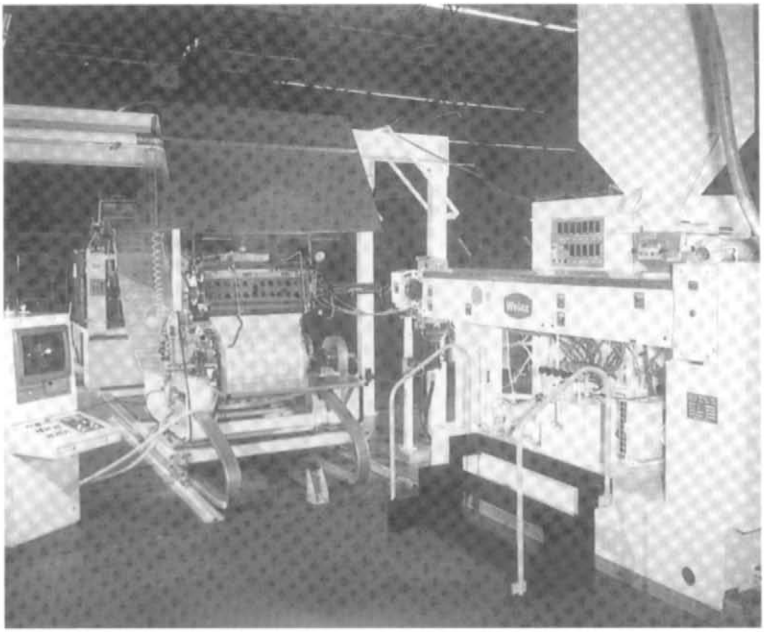
Leading the processing growth was the expansion of twin-sheet and pressure-formed plastic products. Fueled mostly by advances in mold technology, material developments, and thermoforming machinery capabilities, technology improvements in the form of machine controls have led to machine designs that are faster and more consistent than was previously possible. As an example advanced materials and machinery enable manufacturers to significantly expand their culinary market share producing high-performance containers for home and fresh food.

Annealing takes place after the formed part is produced. This heat treatment is directed at improving performance by removal of those sections that contain stresses or strains set up in the material during its fabrication. Depending on the plastic used, it is brought up to a required temperature for a definite time period, and then liquid (usually water; also use oils and waxes) and/or air-cooled (quenched) to room temperature at a controlled rate. The temperature is near the melting point. At the specified temperature the molecules have enough mobility to allow them to orient to a configuration removing or reducing residual stress. Annealing is generally restricted to thermoplastics, either amorphous or crystalline. Result is increasing density, thereby improving the plastic's heat resistance and dimensional stability when exposed to elevated temperatures. It frequently improves the impact strength and prevents crazing and cracking of excessively stressed products.

The plastic that is used is produced usually by extrusion (Chapter 5). A small amount is calendered (Chapter 9) or cast (Chapter 16). The sheet can either pass directly from the extruder to the thermoformer (Figure 7.2) or can pass through an intermediate storage phase. During storage, the sheet is held at room temperature and is reheated before forming, so this two-stage process is known as reheat forming or cold forming. The alternative single-stage process is known as inline forming or hot forming.

When extrusion and thermoforming are separate operations, the high heat energy supplied for extrusion is completely lost by chilling the sheet. Reheating for thermoforming requires additional heat energy. The in-line process offers using a high percentage of the energy/heat already contained in the sheet to condition it to the forming heat. Savings of about 30 to 40% can actually be obtained. The in-line process also provides a more even heat distribution followed with weight distributions that can be reduced without changing physical properties. At equal output rates, an in-line process needs only at least half the floor space when compared to the separate operations.

Control improvements have provided more consistent heating capabilities. Some heater manufacturers have developed or refined their manufacturing processes, while others have developed new heating systems, such as gas catalytic panel heating systems, to provide the industry with more effective heaters - and more heater-to-heater temperature consistency.[476] This type of technology permits innovative mechanical



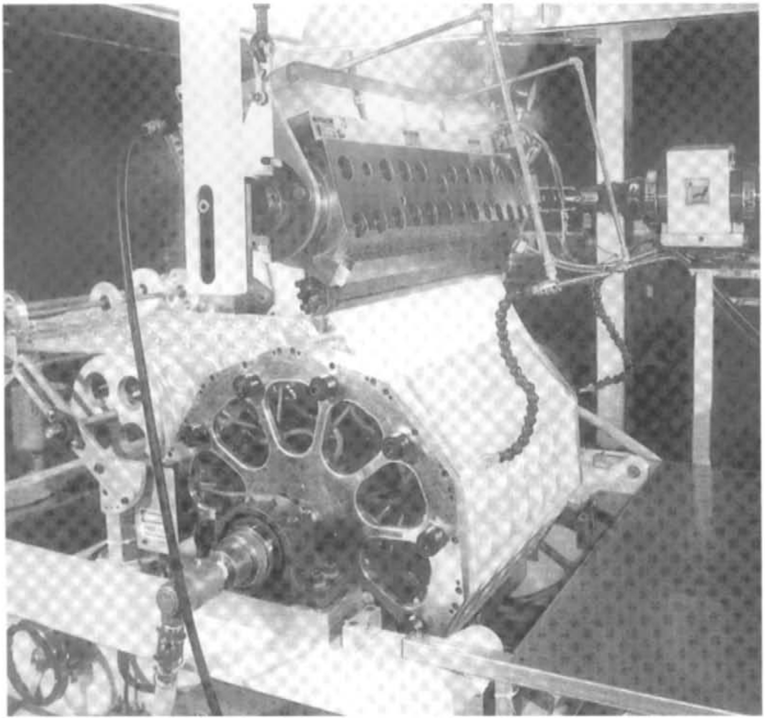


Figure 7.2 (1) In-line high-speed sheet extruder feeding a rotary thermoformer and (2) view of the thermoforming drum (courtesy of Welex/Irwin)

designs such as adding a third forming station to a double-ended thermoformer, and six-station rotary thermoformer to meet customer cost/performance requirements. Table 7.1 provides a comparison of different heaters.

Table 7.1 Comparison of thermoformer heaters

Heater Type	Advantages	Disadvantages
Tubular metal rod (Calrod)	Low cost, durable, rapid heat-up, easy to clean	Rapid loss in efficiency, difficult to control, needs reflectors, reflectors must be cleaned, rust, difficult to zone
Tubular quartz	Fastest heat-up, excellent zoning, wide wattage range	Fragile, can be pitted
Ceramic	Durable, good zoning, lower cost, good temperature control	High installation cost, hard to find burned-out elements, below average temperature -response time
Electric panel	Stable heat, available with quartz cloth, metal, ceramic faces; installation easy	Large size, high replacement cost
Catalytic gas	Uniform heat, low operating cost, gas company may subsidize	Large size, difficult to zone, very slow temperature response, very high installation cost
Non-catalytic gas	Inexpensive energy source, very durable	High installation cost, intense energy source, can cause fires, restricted to heavy-gauge
Halogen	Pulsed heat, fastest heat-up, excellent zoning, very small elements	Fragile, very expensive, high installation cost, unknown reliability

Other technology improvements, such as position control for electric platens, as well as the speed capabilities of electric drive systems for platen-drive systems, sheet-wheel rotate systems, and sheet-car transfer systems, have provided faster and more consistent machinery for fabricators to operate. Use is made of the latest in computer design technology to ensure both the electrical and mechanical design integrity of all its equipment and to upgrade the systems it provides for all its customers. These include a full array of services for cut-sheet and roll-fed customers including new equipment.

Practically any thermoplastic can be used. However certain types make it easier to meet certain forming requirements such as deep draws without tearing or excessive thinning in areas such as corners. Ease of thermoforming depends on the type of plastic used and minimizing plastic's thickness tolerance. More than 80wt% of the thermoformed plastics are amorphous (Chapter 1). The styrenic family of plastics represents approximately 80wt% of the thermoformed amorphous plastics. Disposable, thin-gauge products represent approximately two thirds of their consumption, with the rest being permanent, heavy-gauge products.

The following TPs are the main thermoforming materials processed: high-impact and high-heat PS, HDPE, PP, PVC, ABS, CPET, PET, and PMMA. Other plastics of lesser usage are transparent styrene-butadiene block copolymers, acrylics, polycarbonates, cellulosics, thermoplastic elastomers (TPE), and ethylene-propylene thermoplastic vulcanizates. Coextruded structures of up to seven layers include barriers of EVAL, Saran, or nylon, with polyolefins, and/or styreneics for functional properties and decorative aesthetics at reasonable costs.[239–241]

Films (<10mil, <250grn) of formable plastics exhibit different behavior depending on the plastic. Examples include where PS is unstable with heat and requires extra cooling. PVC and PVDC are excellent, with no restrictions. Nylon is difficult.[437] PCTFE is sensitive to heat and pressure fluctuations. HDPE is difficult without a support film. PP has a very narrow heat range. PET is an example involving large production quantities. To make it formable, researchers produced crystallized PET (CPET). Other important materials are coextruded sheets. These multilayer-extruded materials provide synergism between physical properties and chemical resistance. They include barrier layers of ethylene-vinyl alcohol (EVOH) copolymers and others, including those required for aseptically packaged food products with a long shelf life at room temperature.

Thermoforming machines range from small to very large that can handle precut sheets to continuous sheet feed from a roll (Figure 7.3) or directly from an extruder into a continuous operating thermoforming machine. Classification of machines is usually by the number of operations they perform such as single-stage, double-stage, three-stage (Figures 7.4), five-stage (Figures 7.5), and rotary. There are special designed thermoforming machines that starts with plastic extruded tube, flattened by rolls, and formed in molds on a rotary wheel.

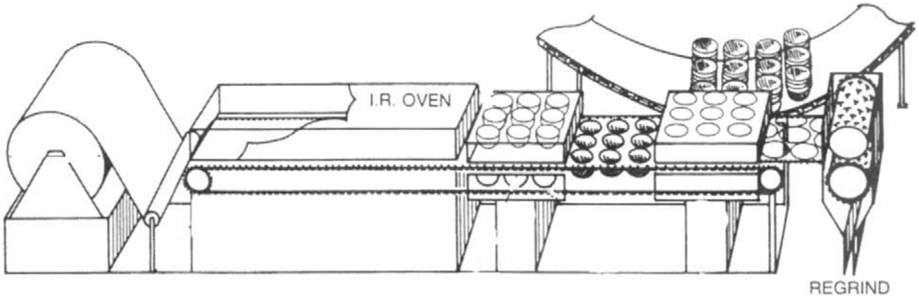

I.R. OVEN
REGRIND

Figure 7.3 Schematic of roll-fed thermoforming line

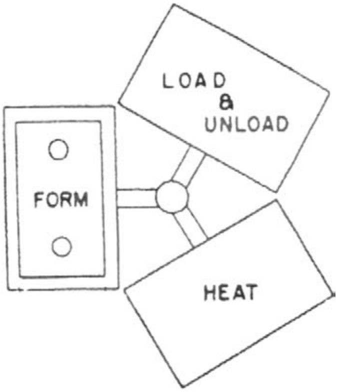

LOAD
&
UNLOAD
FORM
HEAT

Figure 7.4 Schematic example of a rotating clockwise three-stage machine

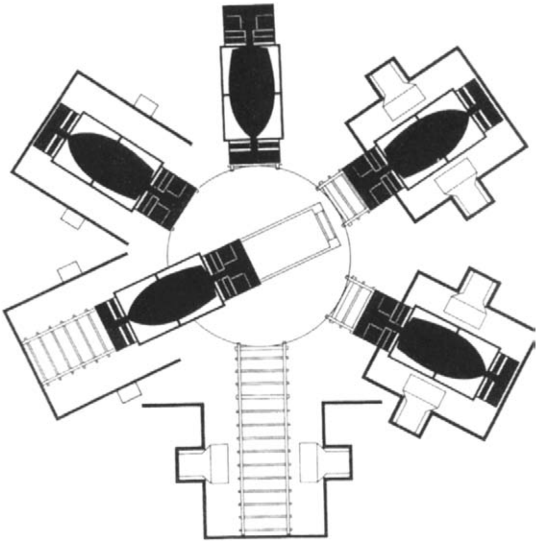


Figure 7.5 View of a rotating clockwise five-stage machine (courtesy of Wilmington Machinery)

Mold

The three general mold shapes are male or positive, female or negative, and mixed having both positive and negative characteristics. Parts drawn over male molds tend to have greater draft angles, heavier bottoms and corners, and thinner rims with the inside of the product replicating the mold surface. Parts drawn into female molds tend to have smaller draft angles, thinner bottoms and corners, and heavier rims, with the outside of the product replicating the mold surface. Prestretching, particularly plug assisting, is easier to use with female molded products. Mixed products must be designed with the characteristics of both male and female elements in the mold design.

When prestretching the hot sheet before forming on a mold usually 3 to 5 psi compressed air is used resulting in a greater amount of air being at atmospheric pressure than in the processing of non-stretched parts. Two important requirements in the forming cycle are to sustain the pressure and to maintain uniform heat in the plastic. Faster air evacuation produces higher quality products.

Many molds have common assembly and operating parts with the target to have the tool's cavity designed to form the desired final product shapes and sizes based on the plastic characteristics such as degree and direction of shrinkage. A mold can be a highly sophisticated/expensive piece of equipment. It can comprise of many parts requiring high quality metals and precision machining. To capitalize on its advantages, the mold may incorporate many male or female cavities, adding further to its complexity. Some thermoforming molds have been preengineered as standardized products that can be used to include cavities, heat/cooling lines, mechanisms for trimming and/or unscrewing, etc. This action is a take-off of the extensive preengineered standardized molds for injection molding (Chapter 17).

The thermoforming mold performs two equally important functions. It defines one surface of the product, and it acts as heat exchanger to cool the product rapidly from the forming temperature to ejection temperature. The cooling function has a direct relation on process economics. It continues to be more efficiently performed even though difficulties exist. One basic difficulty is that all heat must be extracted through one surface of the product. Because contact between the mold and the product is not intimate an insulating space develops. Space that exists significantly reduces rate of cooling and can cause problems such as nonuniform cooling with uneven stresses remaining in the plastic. Slowing up the cooling rate will eliminate problems but extends the cooling cycle times resulting in increased costs.

The heat exchange function of the mold leads to a conflict of interest. Thermoforming is carried out at relatively low pressures, very low pressures in the case of vacuum forming, so molds can be constructed from light, inexpensive, easily shaped materials such as wood, plaster, or epoxy resins. However, these materials have poor thermal conductivity. Thus such molds do not function well as heat exchangers.

Consequently, their use is best confined to short run or prototype use. In normal production, the improved heat transfer capability of a metal mold will more than repay the greater cost. Aluminum is most commonly used for thermoforming molds; other options include cast or sprayed low melting point alloys, porous sintered metals, and copper alloys (Chapter 17).

The molds can include channels for the circulation of cooling water. Because the forming process is performed at relatively low pressure, the channels can, depending on the material of construction and the actual working pressure, approach within about 10 mm of the forming surface for greater cooling efficiency. In the case of a cast or sprayed mold, the cooling channels can be prefabricated in copper pipe to follow closely the cavity contours.

The principal decision to be made when designing a thermoforming mold is to determine which of the two product faces is to be defined by the mold. As so many thermoformings are containers and are substantially cup or box-shaped, this decision determines whether the mold is to be of the male or female type. The shape of a thermoforming is sharply defined only on the surface in contact with the mold, so whichever is the primary presentation face of the product may determine the mold strategy.

When the forming may be produced from a sheet with a grained or textured surface, the mold may be designed to define the second surface of the product in order to preserve the sheet surface. Another consideration is to simplify the production process and machinery, and here the best choice is usually a female mold because sheet clamping is easier to arrange and machine. Female molds also have the advantage when multiple cavities are to be placed close together. When male cores are closely spaced, there is a risk of the sheet bridging between cores and either failing to conform fully to the mold or becoming excessively thinned or even ruptured. Shrinkage also makes it easier to release the forming from a female mold than from a male.

The cavity surfaces should be finely sand blasted to prevent formings from sticking in the mold. The mold requires a multiplicity of vacuum or vent ports, and these should be distributed across the forming surface and must also be carefully sited in ribs, slots and other features that are likely to become isolated as the forming sheet progressively seals off the other ports. The ports must be small in diameter, so that little or no trace of their presence is transferred to the product as a witness mark. One rule is to make the vent diameter smaller than the thickness of the forming at that point, subject to a maximum diameter of 0.3 mm. The vents are relieved from the back of the mold by a much larger bore or a series of diminishing bores, drilled to within about 2 mm of the mold face.

Forming mold may include two other important features. Pre-stretch plugs are designed specifically for a particular mold contour and should be regarded as an integral part of the mold design. There is an increasing tendency, too, for product trimming to be built into the thermoform tooling, either by means of a peripheral knife-edge around the mold form or by providing an integral punch that separates the product by shearing it from the sheet. The advantage is that there is no possibility of sheet shrinkage producing a misalignment between the product and the trimming action. The disadvantage is that in-mold trimming increases the mechanical complication and cost of tooling, so the technique tends to be confined to high volume packaging applications.

Certain basic facts must be observed in the manufacture of molds. Flat surfaces should be avoided if possible, because slight domes or dish effects will allow the sheet to stretch over the entire surface. The curved surface prevents the slight bumps that usually may appear in flat sections. Maximum allowable vent hole diameters will vary with materials and sheet thickness. Air evacuation holes should be as small as possible and to minimize restriction of plastic flow through vent holes, the openings should be back drilled mold surface, as reviewed above.

The total number of vent holes depends on the desired rate of drawing. Since it is usually desirable to form as rapidly as possible, a number of holes should be provided based on trial and error method and/or experience. A combination mold with several cavity sections (such as with large formed products) requires an increase in the ratio of holes to a cavity chamber volume in order to permit evacuation of a deep chamber more rapidly than an adjacent shallow section.

Rapid plug assist forming also requires an increase in the number of vent holes. Vent holes should be at least be located in those areas into which the sheet will be drawn last. In vacuum forming they project downward into a common chamber at the bottom of the mold. In parts where fine detail or textured patterns must be accurately reproduced, vent holes less than 0.5 in. (0.013 cm) apart is usually necessary.

Undercuts used in a mold require them to provide a means to easily remove the formed product. Use of split section molds can be designed to be disassembled permitting removal of the product. Other approaches include hinged sections that unfold as the part is removed may be used for straight-line undercuts. Protruding sections that are cam-actuated may be withdrawn into the mold before the product is removed. Mechanical strippers may be used in the mold to provide positive mold release for products having slight undercuts, particular in high-speed production operations.

Where applicable an undercut insert in the mold can remain as an insert in the finished part. Such inserts can be held in place by the undercut. If possible, they should be made from the same material used in forming the part so there will be no difference in thermal expansion and contraction.

Male molds provide for tighter tolerance controls. What causes female molds to have more difficulty in controlling tolerances is due to plastic shrinking away from the mold during cooling. Prestretching or extended localized heating can be used with either type mold to provide a more uniform wall thickness.

The female molded product has the greatest wall thickness with the thinnest bottoms. The reverse occurs when using a male mold. During the forming, the part of the hot sheet that touches any part of the mold will start to cool resulting in a thicker wall with possible frozen stresses. With multiple cavities the female mold permits the cavities to be spaced closer together. Costwise the lower cost is a male mold.

Processing

Different processes are used to thermoform plastic products that range from manual too fully automatic. Some of these processes with different names tend to have overlapping techniques. Choosing the optimum process encompasses a broad spectrum of possibilities. Sometimes only one process can be used, but generally there are options. Influencing the selection are quantity, size, thickness, tolerances, type plastic used, performance requirements, design optimized, cost limitations, and so on. As an example plastics with fillers and/or reinforcements are generally far more stable in meeting tighter tolerances. Processing may involve equipment that is simple to operate, or it may require extensive specialized equipment along with all types of auxiliary equipment (Chapter 18).

Special processes developed when certain plastics required handling that is normally unavailable with conventional thermoforming machines. Most of these methods tend to reduce the required heat or even eliminate it entirely. One popular technique is high-pressure forming, which is like conventional compression forming or compression molding (Chapter 14). Many of the techniques that are used have been modified in the past from conventional metalworking forming tools. These methods are cold forming (performed at room temperature with unheated tools), solid-phase forming (plastic is heated below the melting point and formed), and compression molding of reinforced/composite sheets (using heat). Other methods are classified as forging (including closed-die forming, open-die forming, and cold pressing), stamping, rubber pad or diaphragm forming, fluid forming, coining, spinning, explosive forming, scrapless forming, and so on. Figure 7.1 can be used as a guide to the following processes being reviewed.

Vacuum Forming

A heated sheet forms part of a closed cell with a mold cavity. When the air in this cell is evacuated, atmospheric pressure forces the sheet into contact with the mold.

Pressure Forming

Process is faster than vacuum forming and provides a more clearly defined detail on finished parts than straight vacuum forming. Certain plastics require this faster forming method such as oriented polystyrene (OPS). Air pressure is used, thus requiring molds capable of withstanding the pressures applied. Also, a clamped sealable pressure chamber is needed, as well as equipment capable of withstanding the pressure forces. When air pressure is admitted to this cell chamber, the sheet is forced into contact with the mold form. During this operation, air must be expelled from the space between the sheet and the mold form. This is done either by venting the space to atmosphere through a series of small ports in the mold, by evacuating the space by vacuum means, or by a combination of both.

When exerting forming forces in excess of atmospheric pressure, pressure forming processes greatly expand the design envelope and market applications for thermoforming. Much thicker and stronger sheets can be formed, the replication of mold surface detail is greatly improved, and it becomes possible to form relatively sharp corners and undercut features.

Vacuum-Air Pressure Forming

There are different forming techniques that use this combination. Air flow and air pressure is used to preform a heated sheet prior to the final pull-down onto the cavity using vacuum. This is a takeoff of combining pressure forming and vacuum forming.

Blow Forming

Method of shaping thermoplastic sheets such as PMMA, PC, and CA using compressed air. Process consists of securing the edges of a heated sheet to a metal backing plate and applying about 15 psi (100 kPa) internal pressure to blow to a desired shape such as hemispherical building bubble and elongated aircraft canopy bubble.[449]

Drape Forming

Drape forming process is the simplest technique for use with a male mold. The heated clamped sheet is lowered over the mold until it seals with the mold base. This action allows the heated sheet to conform by gravity or pressure. The mold form acts as a crude sheet pre-stretch plug.

Drape-Vacuum Forming

It combines drape forming with vacuum action. The sheet is clamped into a movable frame, heated, and draped over high points of a male mold. Vacuum is pulled to complete the forming operation. In this technique a male or female mold is closed into the hot sheet.

Drape Vacuum Assist Frame Forming

A frame, made of anything from thin wires to thick bars, is shaped to the peripheries of the depressed areas of the mold and suspended above the sheet to be formed. During the forming, the assist frame drops down, drawing the sheet tightly into the mold. This action prevents webbing between high areas of the mold and permitting closer spacing in multiple molds.

Drape with Bubble Stretching Forming

It is a modified system of drape forming for producing more uniform wall thickness and minimizes the dangers of tearing over the corners of large moldings because of the protective cushion of compressed air above the rising mold. The film or sheet is heated and blown into a bubble so that the sheet is prestretched before forming.

Snap-Back

Vacuum (or pressure) is used both to billow pre-stretch and to form the sheet. The heated sheet is first clamped across a vacuum box or chamber, which is then partially evacuated, causing atmospheric pressure to billow and stretch the sheet. A male mold is then advanced into the billowed sheet, and forming is completed by drawing a vacuum (or pressure) on the mold while venting the vacuum chamber to the atmosphere. The process is a takeoff to drape forming but with the advantage of sheet pre-stretch, which produces a much more uniform distribution of wall thickness.

Plug Assist Forming

Heated sheet is advanced on a shaped plug(s). A multi-cavity mold for cups, containers, etc. will provide plugs for each cavity. As the plug begins to enter the sheet, there may be additional pre-stretch derived from a billow effect around the plug. This is caused by air displaced from the closed cell formed by the sheet and mold and is absent if the cell is vented during the plug assist action. When the plug is fully advanced, the forming is made by forcing the pre-stretched sheet to contact with the mold cavity by the normal vacuum means. Plug-assist techniques are adaptable to both vacuum forming and pressure forming techniques.

Plug assist is used principally when the process is likely to lead to undue variation in the product wall thickness. Plug assist supplies essentially a selective or localized stretch that is related to the specific demands of an individual mold cavity. It is likely to be beneficial when the draw ratio of a product feature is high, and when the product includes edges, corners and other features where excessive stretch and thinning is likely to occur. Plug assist is preferred for plastics with high enthalpy and low thermal conductivity such as polypropylene sheet formed in the solid phase.

It is possible to reverse mold and plug assist from the bottom platen to give better material utilization around the edges. Both cavity and plug-assist forming make possible the production of shapes having protuberances on their inner surfaces, formed in contact with plugs projecting from the interior of the female mold. In the sides of a product, such protuberances constitute undercuts, so that ordinarily the sections that form them must first be withdrawn in order to release the article from the mold. But some undercut articles made from tough flexible sheeting can be sprung out of the mold.

Plug Assist and Ring Forming

Plug functioning as a male mold is forced into a heated plastic sheet held in place by a clamping ring. This is the simplest type of mechanical forming that involves more than a fold into two planes.

Ridge Forming

This is a takeoff of plug assist and ring forming in which the plug is reduced to a skeleton frame that determines the shape of the product. By having the sheet only in contact with ridges of this frame, the intervening flat areas are free from mold surface defects or mark-off and have better surface quality than when formed against a solid mold. If a skeleton frame that surrounds a plane is used, the areas of the formed piece are plane surfaces. In other shapes with ridges that do not fall in a plane, the intervening surfaces tend to be concave. This technique works very well with plastics having high hot strength such as cast acrylics and butyrates.

Billow Forming

To meet different formed products with different processable plastics different variations of this basic process are used. An example is a heated sheet clamped over a billow box (enclosed) chamber. Air pressure in the chamber is used causing the sheet to billow.

Billow Plug Assist Forming

Like the snap back process, billow forming is a sheet pre-stretch process used with a male mold. The sheet is clamped across a pressure chamber and is billow pre-stretched by applying a low magnitude positive air pressure to the chamber. The male mold is then moved into the stretched sheet until the clamp seals on the mold periphery. Contact between the mold and controlling the rate at which the pressure chamber is vented to compensate for the advancing mold can regulate the sheet.

Billow-Up Vacuum Snap-Back

This version of the billow forming method is used with grained or polished stock on a male mold to preserve the surface finish. The forming ring matches the finished product and assists in wiping the stock around the mold as the mold moves into final position. The mold should be run as warm as is compatible with efficient cooling of the product. It is usually a temperature-controlled aluminum mold.

Billow Snap-Back Forming

Different techniques involve the use of a male or female mold and pressure chamber with or without a plug assist in the snap-back process. As an example with a male mold, instead of drawing the hot plastic into the prestretch box, it is billowed into a bubble shape. The height of the billow is usually about 65 to 70% the depth of the part during initial startup and is then adjusted as required. When it is not practical to use a plug assist with a female mold, blowing a bubble and applying fast vacuum can apply a limited amount of prestretching. This is the billow snap technique using a female mold and no plug.

Air Slip Forming

The air slip process uses a positive pressure billow sheet pre-stretch that is generated by the movement of a male mold towards the heated sheet that is clamped across a pressure chamber. The mold platen acts as a piston in the chamber and drives a volume of air ahead of it that serves to billow the sheet. At the full extent of its forward travel, the mold periphery seals against the sheet frame, and forming is completed by drawing a vacuum through ports in the mold.

Air Slip Plug Assist Forming

The air slip technique can be combined with plug assist. An example is where the forming requires both generalized and selective pre-stretching of the sheet. In this case, a plug is advanced into the billowed sheet when the mold is at or near the full extent of its forward travel. A partial venting of the pressure chamber compensates in a controlled manner for the volume displaced by the advancing plug. When the plug pre-stretch is fully extended, drawing a vacuum through ports in the mold completes the forming. The process is particularly suitable for molds that have both male and female features.

Blister Package Forming

Thin plastic film is thermoformed into simple to very complex shapes for packaging different products such candy, fruit, toys, auto parts, etc. Certain packaging products can be used as molds. Machines are used chiefly for skin or contour packaging and blister packaging. Processes can involve the seating of paperboard or plastic to the formed plastic sheet, with the product to be package enclosed. Machines can be equipped to handle skin packaging followed with manual loading operations.

Draw Forming

Process identifies the stretching of a sheet to fit a mold and conform to the mold's cavity shape. It gradually reduces the sheet, film, or other shape of a material by stretching and/or pulling it through devices or perforations in a series of rollers and/or plates to successfully diminish its thickness. They may be cold-drawn (without heat) or hot-drawn (heated to their softening point).

Dip Forming

Dip forming is frequently used for making vinyl plastisol products. The process starts by going through a dip coating operation (Chapter 16). It involves dipping a mandrel into a tank that contains a liquid plastic such as a plastisol and held for a prescribed time so that the heated plastic gels against the form to the desired thickness. Shape of the mandrel simulates the shape of the finished product. The coated form is withdrawn and usually receives a final heat to complete its fusing prior to a sufficient cooling cycle. The coating is stripped off the mandrel. After framing and heating, the stock form is mechanically stretched over a male mold to allow the framed edge to make a seal with the periphery of the mold. This stretching serves to redistribute or preform the sheet prior to application of the vacuum. This process has the major advantages of low cost for both mold and machine, as well as speed of operation.

Form, Fill, and Seal

FFS pouches are used in packaging different liquid to solid products (food, medication and medical devices, soaps, mechanical devices, etc.). They are thermoformed on-line with its contents automatically inserted in the pouch just prior to the sealing action.[244] Sheets or films are formed using a clam shaping procedure using two sheets or a single sheet that is shaped and sealed where the two edges meet to form the pouch just prior to filling. Sealing the package includes the use of heat, adhesive, or their combinations. In certain applications, a liquid product also can be used as a pressure medium to assist in forming followed with a sealing action. Because aseptic features are required for machines of this type, all operations generally are enclosed in pressurized sterilized air chambers.

Form, Fill, and Seal vs. Preform

FFS technology generates a variety of concerns over its visual clarity. Incorporated preforms are typically thick-walled and rigid; this is to protect expensive items packaged, heavy and/or sharp devices, accommodate intricate shapes and compartments, and prevent corner thinning. But thickness is often accompanied by haze. FFSs are usually less thick and rigid than preforms. Although thinness improves clarity, it limits the depth of draw. Hence, FSS is well suited for packaging inexpensive, high-volume products such as syringes and gloves. They do not require much physical properties (as opposed to microbiological properties) protection. When a deeper draw is required as well as clarity, coextrusions are usually the option. There are combinations that are flexible yet tough enough for deeper draws. Nylon plastic is an example.

Form, Fill, and Seal with Zipper In-Line

In the past this type thermoforming technique required a secondary operation where the zipper was added after forming. Since the early 1990s the zipper can be added in-line with the thermoforming action where the zipper is heat-sealed. Speeds of these lines can match those without zippers being added. They provide sealed pouches and bags.

Multiple-Step Forming

There are many variations in multiple step forming, such as combining pneumatic billow and plug prestretching with zoning and pressure forming to meet final product requirements. This process forms heavy-gauge sheet where single parts are often quite complex and deep and where cost considerations make wall thickness uniformity a significant design requirement parameter. Localized non-uniform heating of the sheet, called zoning or patterning, is used to aid in material flowing in the proper directions. Differential pressure is used to form certain filled or short fiber reinforced plastics or to achieve sharp details in neat plastics (Chapter 1). Differential pressures rarely exceed ten atmospheres. Long fiber-reinforced and foamed plastics are frequently too stiff at the forming temperature for pressure molding thus matched die molding or diaphragm molding is used.

Matched Mold Forming

Method requires sufficient driving force of the equipment press platens, proper cavity air evacuation, and a realization of the depth-of-draw limitations. This process can be considered a take-off of compression forming, compression molding, or reinforced plastic (RP) stamping (Chapters 14 and 15). Matched mold forming is a special case of thermoforming that differs from the mainstream in two important respects. The mold defines both surfaces of the finished part, and the forming force is not supplied by air pressure differential across the sheet but by reaction forces generated by a power press acting on the matched mold. The process amounts to compression molding using a sheet preform (Chapter 14). The mold form is reproduced on both halves of the mold, offset by a dimension equal to the sheet thickness.

Solid-State Forming

Solid-state (compression molding approach) forming uses a male metal-plug mold that matches a female metal cavity mold and can be used only with crystalline plastics. Below their glass-transition temperatures (T_g) amorphous resins are generally too stiff to be rapidly formed into stable products (Chapter 1). Crystalline types can be permanently deformed at temperatures between their T_g and their melting point (M_t). Molecular orientation, the mechanism that allows this to occur, relates to the draw ratio. Examples of draw ratios can vary from 5:1 for PET and nylon to 10:1 for low molecular weight PP. The major advantage of solid-state forming is that parts can be produced in very fast cycle times, usually 10-20 s. The surface finish of these products is rather smooth, as the fibers do not surface.

Rubber Pad Forming

Similar to matched metal stamping except that a metal mold half is replaced by a block of solid rubber. Processing material cannot flow to the extent that it can with matched-metal forming. However, more uniform pressure is exerted on the material charge due to the rubber pad.

Mechanical Forming

This process does not use vacuum or compressed air to form the heated sheet. The forces necessary to shape the uniformly heated sheet are applied by mechanical or manual stretching, bending, twisting, compressing, stamping, and/or other devices. Mold components can be used such as mechanically activated undercuts, side pulls, plug assists, etc.

Forging Forming

It is a production method where heated thermoplastic stock or billet material is formed by compression forces or by sharp hammer-like blows. Virtually all ductile materials may be forged and in some cases preheating is not required. When forged below the melt temperature, it is called cold forging, cold forming, or solid-phase pressure forming. When worked above the melt temperature, it is said to be hot forging or hot forming.

Twin Sheet Forming

Twin sheet forming, also called dual sheet forming and clamshell, is a special thermoforming technique. The process resembles blow molding (Chapter 6), except that twin heated sheets are used instead of a tubular extruded parison or injection molded preform. Like a blow molding, the twin sheet forming mold usually consists of matched female mold halves. Molds can include pinch-off zones at the periphery of the cavities. Air pressure through a blowing needle is introduced at a suitable point between the heated sheets, then the mold halves are closed under pressure, welding the sheets into a closed body at the pinch-off zones. Air under pressure forces each sheet into conformity with the corresponding mold cavity face. Thermoforming does not provide the accuracy and tighter measurement tolerance of blow molding but for products not requiring such performance, they provide significant cost advantages.

Cold Forming

This process forms thermoplastic sheet at room temperature. It is a stretching or orientation process used to improve properties, such as tensile strength and modulus of thermoplastic and other materials by orientation of molecules such as in living hinges. This process can change the shape of thermoplastic sheet, film, or billet in a solid phase through plastic (permanent) deformation with the use of pressure dies. Split rotating pressure rolls are used to produce many different extruded-formed shapes such as round, elliptical, square, rectangular, U-beam, I-beam, H-beam, etc. Through the split dies that are under a controlled pressure a continuous plastic extruded profile is pulled.

Process can include heating that is usually well below the plastic's melt or thermoforming temperature. Thermoset (TS) plastics such as B-stage can be used (Chapter 15). The main difference between metal and plastic forming is the time dependency or spring-back, or recovery in thermoplastics. All materials exhibit some strain recovery or spring-back. With TPs, this process depends on temperature, time, and deformation history. For any given forming temperature, holding the part in the deformed state for a given period to allow for stress relaxation reduces the degree and rate of spring-back.

Cold forming and solid-phase forming process plastics such as ABS/PC, PC, conventional PP, and ultrahigh molecular weight high-density (HMWHDPE). By using solid-phase forming, processors can make more efficient use of HMWHDPE plastics that are difficult or impossible to process by other methods. There are thermoplastic reinforced plastic composites that can be formed by stamped to produce high-performance products. Different fiber reinforcements are used (Chapter 15).

Comoform Cold Forming

This is an extension of the cold forming process. It uses thermoformed B-stage thermoset reinforced plastic (RP) skin to improve surface and other characteristics to a cold molded thermoplastic. The mold is closed and the fast, room temperature curing RP plastic system hardens. The finished product has the smooth TP-formed sheet.

Shrink Wrap Forming

A very popularly used product is shrink wrap forming for packaging all kinds of products. The strains developed in a plastic film are released by raising the temperature of the film, thus causing it to shrink over the package where the packaged product acts as a mold. These shrink characteristics are built into the film during its manufacture by stretching it under controlled temperatures to produce orientation of the molecules (Chapter 5). Upon cooling, the film retains its stretched condition, but reverts towards its original dimensions when it is heated around the package. Shrink film gives good protection and excellent clarity.

Scrapless Forming

Different processes have been developed with a few in use. Their designs usually start with an extruded thermoplastic sheet. Circular blanks cut from the sheet are compression molded into the desired preliminary shape. During the compression action, the blank can be simultaneously stretched, or being thermoplastic can be stretched after compression molding. They generate no trim scrap when formed having performances and advantages such as provides an exceptional high degree of molecular orientation, resulting in improved part toughness, stress crack resistance, etc.

Dow's patented scrapless forming process is identified as the SFP process. An extruder produce a biaxially oriented sheet (Chapter 5). In turn the sheet is slit and cut into square blanks. These blanks are heated and pressed into circular disc with a lip. Immediately or latter after reheating, the disc is thermoformed into a shape such as a cup.

Forming and Spraying

Sheet is thermoformed into a product by one of the forming process. To reinforce or rigidize it, one side that is usually the back surface of the formed sheet receives a spray-up of reinforced plastic (Chapter 15).

Solid-Phase Pressure Forming

Conventional PP has the major deficiency of lacking a rubbery plateau at the forming heat; it just sags and falls apart. A process was developed to form PP just below its softening point, avoiding any sag. Known as solid-phase pressure forming (SPPF), it forces PP into the desired shape by mechanical plugs and pressure. Researchers have changed PP to overcome this situation so that conventional forming techniques can be used. Proprietary catalyst and reactor technology extrude thermoformable sheet and film. Material has a rubbery plateau region and a high dynamic modulus, so it is processible in conventional thermoforming machines.

Flow-Compression Forming

Either crystalline and amorphous types (Chapter 1) can be used with flow molding because the plastic is melted prior to forming. The forming temperature is usually lower than for injection molding or extrusion. Plastics need not be trimmed, as the composite is compression-molded to completely fill the mold cavity (Chapter 14). Very important, the flow molding process permits more complex parts to be formed than solid-state forming. The process cycle time is usually about 1 min.

Postforming

Postforming identifies plastic sheet, rods, tubes, and other profile shapes that are formed into different shapes (coils, corrugated tubings, tubular nets, etc. Its major use is inline with an extruder processing thermoplastics. As the plastic exits the die it is formed into different shapes. Details on postforming thermoplastics are in Chapter 5.

Very limited use is made of forming, bending, or shaping B-stage and certain type fully cured C-stage reinforced thermoset plastics that have been heated to make them flexible. On cooling, the formed laminates retain their contours and shape of the mold over which it was formed. The postformed products are subjected to a final higher temperature that cures and solidifies the thermoset plastics (Chapter 15). Generally, only simple shapes are produced by this technique.

Bend Forming

This postforming technique is one of the oldest thermoforming techniques used with TP and TS B-stage reinforced plastic. The bending is relatively easy to handle particularly when it is a straight bend resulting in meeting forming requirements. If the sheet is heated only locally in the bending operation, no special forming tools are needed. The type of material, width of the heating zones, and thickness of the sheet determines the bending radius capability. Limitations or sag of the sheet are related to the softening point of the sheet and the intrinsic rigidity of the heated sheet. Transparent plastics (such as PMMA and PC) are frequently bent for use in store displays, staircases, partitions in banks, aircraft canopies, windows, etc.[446] RTS laminated materials are used in various markets that range from displays to kitchen counter tops.

8 FOAMING

Overview

Foamed plastics are expanded materials with a cellular structure that have various identification names such as plastic foams, cellular foams, expandable foams, structural foams, blown foams, sponges, and microcellular foams.[443, 444] They may be flexible, semi-rigid, or rigid. The usual process involves the introduction of a dispersed gas and subsequently cooling or curing. This technique can make the majority of plastics into foams using most plastic processing methods. Many different products are produced ranging from film or sheet to molded shapes. Many different properties can be obtained based on plastics used [thermoplastic (TP) and thermoset (TS)] and the foam density. Examples of properties are provided in Table 8.1.[1, 2, 246–247]

Their densities usually range from 1.6 kg/m^3 to over 960 kg/m^3 (0.1 lb/ft^3 to over 60 lb/ft^3. They offer an extensive range of physical, mechanical, electrical insulating, and other properties such as different cushioning capabilities. Their performance depends to a great extent on the type of base plastic, type of blowing system, and method of processing. Each plastic can include fillers and/or reinforcements to provide certain improved desirable properties. They are used in different forms such as slabs, blocks, boards, sheets, films, molded shapes, sprayed coatings, foamed-in-place, and extruded profiles.

The growth of plastic foams continues to be significant due to the inherent available properties and usefulness in different applications and environments. The outstanding properties of foamed plastics are their lightweight, low thermal conductivity, and high strength-to-weight ratio. They range from original to replacement parts in buildings, transportation vehicles, sports equipment, boats, underwater crafts, spacecrafts, furniture, decorative displays, toys, and life preservers, and

Table 8.1 Examples of rigid plastic foam properties

Property	ASTM Test	Phenolic		Polyvinyl Chloride Rigid Closed Cell	Phenylene Oxide Foamable Resin	Polycarbonate	Polyethylene Medium-Density Foam	Polystyrene		Polyurethane Rigid Closed Cell
		Foamed in Place	Syntactic Castable					Molded	Extruded	
Density, lb./ft.^{3} (kg/m^3)		2–5 (32–80)	50–60 (800–960)	2–4 (32–64)	50 (800)	50 (800)	5.5–7.0 (88–112)	2.0 (32)	2–5 (32–80)	4–8 (64–130)
Tensile strength, psi (MPa)	D 1623	20–54	1000 (6.89)	1,000 (6.89)	3,300 (22.7)	5,500 (37.9)	110–210 (0.76–1.45)	42–68 (0.29–0.47)	180–200 (1.24–1.38)	90–290 (0.62–2.00)
Compression strength at 10% deflection, psi (MPa)	D 1621	22–85 (0.15–0.59)	8,000–13,000 (55.1–89.6)	——	5,500 (37.9)	7,500 (51.7)	2–18 (0.014–0.12)	25–40 (0.17–0.28)	100–180 at 5% (0.69–1.24)	70–275 (0.48–1.90)
Maximum service temperature dry, °F (°C)		Continuous at 300 225 (149)	275 (135)	—— ——	200 (93.3)	270 (132)	180–200 (82–93)	165–175 (74–79)	165–175 (74–79)	200–250 (93–121)
Thermal conductivity BTU/in./hr.-ft.^{2}-°F (W/mK)	D 2326	0.20–0.22 (0.29–0.032)	1.0 (0.14)	2.0 (0.29)	—— —— ——	—— —— ——	0.32–0.34 (0.046–0.049)	0.23 (0.033)	0.17–0.21 (0.024–0.030)	0.15–0.21 (0.022–0.030)
Coefficient of linear expansion, 10^{-6} in./in.-°F	D 696	5	100	40–60	38	25	——	30–40	30–40	40

their uses and applications continue to advance at a rapid pace. The major plastics used as foams are the polyurethanes and polystyrenes (Chapter 2).

In addition to the basic plastics in liquid and bead forms with foaming agents, fillers, additives that include cell controllers and fire-retardants, catalysts, surfactants, styrene monomer, systems that vary viscosity from liquid to paste form, and other additives are used. The gas can be put directly in to the plastic before the plastic solidifies. Reactant chemicals can be put in the plastic formulation that during polymerization will release a gas and produce the foam.

Very popular are extruding expanded polyethylene, polypropylene, polyvinyl chloride, and polystyrene (Chapter 5). Specially designed extruders can handle a mixture of plastic and a gas foaming agent such as nitrogen. The material expands as it leaves the die. Foaming will take place with a mixture of plastic and blowing agents when put under pressure. Blowing agents used include methyl chloride, propylene, or butylene. A wide range of properties can be obtained in foamed vinyls by just using carbon dioxide. These types of foam materials find applications in the liquid and food serving container consumer markets. Foam sheet made from expandable polystyrene beads containing pentane is extruded.

The technology of polyurethane (PUR) foams has been developing since its inception during the early 1940's in Germany, followed by USA and the rest of the world. This foam packaging material provides specific advantages. It insures firm support and restraint for the product's interior by adapting itself to a product's complex contours. Parts can perform multifunctional use: insulation and load carrying, insulation and ease of application, or buoyancy and structural rigidity. For example, urethane foamed-in-place in a boat hull or hydrofoils makes the vessel virtually unsinkable, reduces noise level, and reduces structural vibration.

Foamed plastics, like their solid counterparts, can be used for almost an unlimited range of products. As an example there are different approaches to spray-foamed homes. Since about the 1950s foamed building structures where fabricated using polystyrene foamed plastics. The initial development was by the US Army. Since then many other foamed structures have been built worldwide using different plastics. An interesting approach was designed and built during 1966. Dome shaped buildings were being built using polystyrene (PS) boards by the Dow's spiral generation technique. Craftsmen heat bond the boards in a continuous pattern to produce the dome shaped medical clinical structures located in Lafayette, Indiana. Boards were heated and bonded at the softening point of the PS in order to form a continuous pattern that produces the dome shape. Sections cut from the dome were made into doors, connecting halls going from dome to dome. These domes are structurally self supporting, requiring no internal or external support during or after manufacture. It also provides its own insulation and other advantages.

Similar to other materials, foams have limitations. No foam is fireproof but many of them can be made flame-resistant. Phenolics and silicones have excellent heat resistance but could crumble when subjected to vibrational stress if not modified. There are foams that can be affected by solvents, but fluorinated types resist them. However these plastics with modifiers provide acceptable performances.

There are various combinations of plastics and blowing agents to fabricate different products. Basically during the process a blowing agent expands the plastic initiating cells that grow to produce the final foam. As gas is produced equilibrium is established between material in the gas phase and the material dissolved in the solid state. The gas dissolved in the solid state migrates from the solution into the gas phase. The cells formed are initially under higher than ambient pressure because they must counteract the effects of the plastic's surface tension. The pressure due to surface tension depends on the reciprocal of the cell radius so the pressure within the cell is reduced as the cell grows. Different techniques are used to control this foaming action.

Small cells tend to disappear and large cells tend to get larger. This is because the gas migrates through the matrix or substrate (plastic) or the cell walls break. After forming cells, the foam has to be stable; the gas must not diffuse out of the cell too quickly, thereby causing collapse or excessive shrinkage. The stability of the foam depends on the solubility and diffusivity of the gas in the matrix. The many processes make for many methods of cell initiation, cell growth, and cell stabilization.

Foam structures consist of at least two phases, a plastic matrix and gaseous voids or bubbles. A closed-cell or open-cell structure is formed, with cellular walls enclosing the gaseous voids. In closed cell foams, the gas cells are completely enclosed by cell walls, while in open-cell foams, the dispersed gas cells are unconfined and are connected by open passages. Plastic can be stabilized against cell rupture by crosslinking (Chapters 1 and 2).

A basic distinction is made between closed-cell systems, where spherical or roughly spherical voids (cells) are fully separated by matrix material, and open cell systems where there are interconnections between voids.

The degree of interconnection can be assessed if a sample is subjected to a moderate vacuum; a liquid is then allowed to fill the interconnected spaces and the weight gain is measured. The cell size or average cell size can be an important factor. A distinction is sometimes made between microcellular foams 0.1 to 10 micron diameters. They correspond roughly to cells indistinguishable with the naked eye and macrocellular foams (at least 250 micron). With microcellular foaming products can be produced that are lightweight, high strength, and are thin walled (such as 0.5 mm thick).

The cell density (number of cells per unit cross-section area or volume) is also used to characterize the coarseness or fineness of foam. Foamed products can feature a deliberately created inhomogeneous (nonuniform) morphology. An example is when a foamed core is sandwiched between solid skins as in so-called structural foams, or in elastomeric products with so-called integral skins. With cells elongated in the direction of foam rise or melt flow, the process will give an anisotropic structure and properties (Chapter 15).

Blowing agent

Different foaming agents (also called blowing agents) are used to produce gas and thus to generate cells or gas pockets in the plastics. The type of blowing agents used influences all kinds of physical, mechanical, electrical, thermal conductivity, and other properties. The amount of blowing agent used affects the properties of the foamed plastic, and different amounts are required for particular applications.: about 0.1wt% for elimination of sink marks in injection molded parts, 0.2 to 0.8% for production of injection molded structural forms, 0.3% for extruded foamed profiles, 1 to 15% for formation of vinyl foams, and 5 to 15% for compression-molded foam products. Nucleating and cell-sizing agents can be added to produce cells of a more uniform size and to enhance the symmetrical expansion of cells during the foaming process.

Foaming methods vary widely. One is to whip air into suspension or a solution of the plastic, which is then hardened by heat curing. A second is to dissolve a gas in a mix, then expand it when the pressure is reduced. Another is to heat a mixture until one of its liquid components volatilizes. Similarly, water produced in an exothermic chemical reaction can be volatilized within the mass by the heat of reaction. A different technique uses a chemical reaction to produce carbon dioxide gas within solid mass. A related way is for a gas such as nitrogen to be liberated within a mass by thermal decomposition of a chemical blowing agent. Other techniques disperse small solid particles, tiny beads of plastic, or even glass microballoons within a plastic mix or syntactic foam.

The most common method disperses a gaseous phase throughout a fluid plastic phase then preserves the resulting combination, this is called the dispersion process. The expansion process consists of the following actions:

1 creation of small discontinuities or cells in a plastic fluid phase,

2 growth of these cells to a desired volume,

3 stabilization of the resultant cellular structure by physical or chemical means. The gas phase is usually distributed in voids or pockets called cells. They can be foamed open-cell but usually they are foamed closed-cell.

The most popular blowing agents are classified as physical or chemical, depending on how the gas is generated. Physical blowing agents (PBAs) undergo a change of state during processing, while chemical blowing agents (CBAs) usually solids, undergo a decomposition reaction during processing that results in formation of a gas. PBAs are compressed gases or volatile liquids. Compressed gases, usually nitrogen, are injected under high pressure such as 2,000 psi, into the plastic melt during processing. As the pressure is relieved, the gas becomes less soluble in the plastic melt and expands to form cells. Nitrogen is inert, non-flammable, and can be used at any processing temperature. No residue is left in the foamed plastic, so that recycling of the plastic part is easy. When using compressed nitrogen, however, generally the result is to produce foams with a coarser cell structure and poorer surface appearance than nitrogen produced with CBAs, although nucleating agents can be added for a finer cell structure.

There are liquid PBAs that are volatile and change from a liquid to a gaseous state when heated to the plastic processing temperatures. They are short-chain chlorinated and fluorinated aliphatic hydrocarbons (CFCs). Although they can be used over a wide temperature range and at low (atmospheric) pressures, they have been gradually discontinued due to their role in the reduction of stratospheric ozone.[249] Other PBAs are reviewed in Table 8.2.

Chemical blowing agents (CBAs) decompose at various processing temperatures to form a gas (Table 8.3). The most important criterion for selection of a chemical blowing agent is that the decomposition temperature matches the processing temperature of the plastic. Little or

Table 8.2 Examples of physical blowing agent performances

Blowing agent	Molecular weight	Boiling point (C)	Blowing efficiency At boiling point	Blowing efficiency At 100 C
Pentanes				
n-Pentane	72.15	36.1	216	261
2,2-Dimethylpropane	72.15	9.5	196	260
1-Pentene	70.15	30.0	227	280
Hexanes				
n-Hexane	86.17	68.7	212	232
2-Methylpentane	86.17	60.2	207	232
3-Methylpentane	86.17	63.3	211	234
2,2-Dimethylbutane	86.17	49.7	204	229
Cyclohexane	84.17	80.8	266	281
Heptanes				
n-Heptane	100.20	98.4	206	207
2,2-Dimethylpentane	100.20	79.2	193	204
2,4-Dimethylpentane	100.20	80.6	193	204
3-Ethylpentane	100.20	93.4	204	212
Toluene	92.13	110.6	294	286
Trichloromethane	119.39	61.2	342	382
Tetrachloromethane	153.84	76.7	296	316
Trichlorofluoromethane	137.38	23.8	261	329
Methanol	32.04	64.6	679	752
Isopropyl ether	102.16	67.5	198	217
Methyl ethyl ketone	72.10	79.6	324	344

Table 8.3 Examples of chemical blowing agents

Chemical Name	Decomposition Temperature (°C)	Gas Yield (cm^3/g)	Type	Typical Foamed
Azodicarbonamide (AZ)	195–215	220	Exo	EVA, HDPE, LLDPE, LDPE, PP, TPE, FPVC
4,4'-oxybisbenzene sulfonyl hydrazide (OBSH)	160	125	Exo	HDPE, FPVC
p-toluenesulfonyl semicarbizide (TSS)	228–235	140	Exo	EVA, HDPE, LLDPE, LDPE, PP, TPE, FPVC
5-phenyltetrazole (5-PT)	250–300	200	Exo	PP, PC
Sodium Bicarbonate (NaHCO$_3$)	100–140	135	Endo	LDPE, EVA, FPVC, TPE
Alkali Carbonate (Hydrocerol)	160+	100–160	Endo	LDPE, EVA, LLDPE, FPVC
Alkali Carbonate (Activex)	120	140	Endo	LDPE, EVA, FPVC
Alkali Carbonate (Safoam)	170–210	130	Endo	EVA, HDPE, LLDPE

no foaming will occur at processing temperatures below the decomposition temperature. With processing temperatures too high the result can be in overblown or ruptured cells and poor surface quality.

Activators such as alcohols, glycols, antioxidants, and metal salts, can be added to lower the decomposition temperature. Other selection considerations include the type and amount of gas liberated and its effect on the final product.

CBAs can be classified as inorganic or organic. Their decomposition can be endothermic or exothermic. Endothermic blowing agents, usually inorganic, require the input of energy for the decomposition reaction to take place, while exothermic blowing agents, usually organic, release energy during decomposition. Exothermic CBAs commonly have a higher gas yield than endothermic CBAs. The lower gas yield and pressure associated with endothermic CBAs produce foams with a smaller cell structure, resulting in improved appearance and physical property performance. Endothermic and exothermic CBAs have been combined in a single product, in which the exothermic CBA provides the gas volume and pressure necessary for lower densities, and the endothermic CBA produces a fine, uniform cell structure.

CBAs are available as dry powders, liquid dispersions, and pellet concentrates. They can be incorporated by dry-blending with the resin powder, tumble-blended with resin pellets, blended using a hopper blender, metered in at the feed throat, or pumped into the barrel. Typical inorganic blowing agents are sodium bicarbonate, sodium borohydride, polycarbonic acid, and citric acid, which primarily evolve into carbon dioxide gas upon decomposition. Sodium bicarbonate is the most common inorganic blowing agent. It is inexpensive, and it decomposes endothermically at a low temperature, over a broad temperature range (100 to 140C (212 to 284F). At temperatures ≥142C (287F), decomposition becomes more rapid, facilitating its use in polyolefins. Its decomposition is less controllable than organic blowing agents, however, and it can form an open-celled foam structure. Its gas yield is 267 cc/g. Polycarbonic acid decomposes at about 160C (287F), with a gas yield of about 100 cc/g. It is also used as a nucleating agent in physical blowing agents.

Organic CBAs evolve gas over a specific, narrow temperature range and are selected according to the processing temperature of the plastic. The most common low temperature blowing agent is 4,4′oxybis benzenesulfonyl hydrazide) (OBSH), with a decomposition temperature of 157 to 160C (315 to 320F) and gas yield of 125 cc/g. High temperature blowing agents, with decomposition temperatures of greater than about 230C (450F), include 5-phenyltetrazole, with a decomposition temperature of 240 to 250C (460 to 480F) and trihydrazine triazine (THT).

As an example azodicarbonamide (ABFA), with a decomposition temperature of 204 to 213C (400 to 415F) is commonly used in PP (melting temperature is 168C; 334F). The use of activators can reduce the decomposition temperature to 150C (300F). ABFA is a yellow powder that decomposes exothermically, with a gas yield of about 220 cc/g, to produce a gas mixture containing 65% nitrogen. ABFA produces a fine, uniform cell structure but can produce discoloration in the foamed part. It is nontoxic and is FDA-approved for a wide variety of applications, including those involving food contact. The high gas yield, good performance, and low cost of ABFA make it a widely used foaming agent.

Other agents used include p-toluenesulfonyl semicarbazide (TSSC), although it decomposes at an intermediate-to-high temperature [228 to 236C (442 to 456F)]. Activators can be used to decrease the decomposition temperature. It has a gas yield of about 140 cc/g; the gas mixture consists of nitrogen, carbon monoxide, carbon dioxide, and trace amounts of ammonia. Its white color and nonstaining residue are important in applications requiring color quality. It is flammable and burns rapidly when ignited, producing a large amount of residue.

The overwhelming majority of foams are TPs, but TSs are also foamed with CBAs, although some of them do create problems. Popular TS foams are made from polyurethane, polyester, phenolic, epoxy, and rubber. Thermal decomposition of the blowing agent with certain plastics such as TS polyesters cannot be applied in this system because the heat of polymerization is not high enough to induce decomposition. But chemical reactions simultaneously produce gas and free radicals; they typically involve oxidation and reduction of a hydrazine derivative and peroxide. The reactions are catalyzed by metals, which can be used repeatedly.

Polyurethane foams (often referred to as urethane foams) are prepared by the reaction of a polyisocyanate with a polyol in the presence of a blowing agent, a surfactant, and a catalyst without external beating of the foaming system. The principle of preparation of urethane foams is based on the simultaneous occurrence of two reactions, i.e., polyurethane formation and gas generation in the presence of catalyst and surfactant. In flexible urethane foams, the major blowing agent is water and, at the same time, auxiliary blowing agents. An example of a PUR foam mix is the polyol, polyisocyanate, chemical blowing agent, catalyst, and surfactant that generates gas and produces PUR foam.

With the ban on the use of CFCs (chlorofluorocarbons) major changes in foam formulations developed.[249] A number of studies were carried out on the use of 100% water-blown foams for both rigid and flexible foams. Other agents included pentane. These studies required modifications or improvements in raw materials (such as polyisocyanates, polyols, catalysts and surfactants).[251, 438, 468]

The polyisocyanates which can be used for preparing isocyanate-based foams are mainly aromatic compounds and some aliphatic or aralkyl polyisocyanates. TDI (toluene diisocyanate) is widely used for flexible foams. Pure MDI (diphenylmethane diisocyanate) is used for elastomers and coatings. Modified TDI and modified MDI are used for high-resilience flexible foams. Polymeric isocyanates (polymeric MDI or oligomeric MDI) are mostly used for preparing rigid urethane and isocyanurate foams, and in part, for preparing flexible and semi-flexible foams.

Water may at first appear to be an unlikely blowing agent for plastic foams because of its low volatility and low solubility compared to CBAs.[249] However, because manufacturers have started to realize the cost, storage, handling and environmental benefits of using water, its use as a blowing agent has increased. They offer reduction of product weight and increased production rate opportunities. In addition, the components are recyclable and exhibit excellent long-term physical properties for sealing and weathering. Water foaming can be accomplished by modifying a standard single screw extruder. Special requirements are focused, as with other blowing agents, on precise metering of water injection, temperature control, and mixing of the water with the plastic such as TPE. Liquid temperature control of barrel zones and a minimum of a 30:1 L/D extruder are usually required. Water injection takes place at the 18:1 L/D position with a pump capable of at least 10 MPa with an adjustable flow rate up to 10 ml/min.

Chlorofluorocarbon and Alternate

CFCs are a family of inert, nontoxic, nonflammable, and easily produced liquefied chemicals that have principally been used in refrigeration, air conditioning, packaging, and insulation or as solvents and aerosol propellants (medical and other devices). The plastics industry, as well as other industries, has been phasing out CFCs,[252] which were once widely used in producing foam products.[249] CFCs chlorine components reportedly destroy ozone in the upper atmosphere. A targeted worldwide complete phase-out of CFCs was soon among the amendments to the Montreal protocol approved unanimously by 93 nations at a 1987 meeting in London. Participating nations also agreed to use hydrochlorofluorocarbon (HCFC) only where other alternatives were not feasible. The alternative HCFC (hydrochlorofluorocarbon) is 98% less ozone depleting than CFCs.

Fully halogenated CFCs were eliminated in polystyrene foam food packaging and containers. Substitute blowing agents used are either no threat to the ozone or are a 95% improvement over fully halogenated CFCs. Action has been taken such as where PS foam cups now are 100% CFC-free, etc.

Type of foam

Not all types of plastic foams possess all properties in the desirable ratio. As an example, those of most interest to hospitals are polyurethane PUR) and vinyl (PVC) foams. The latter compete with foam rubber and PUR foam as cushioning and padding material. Among the advantages of PVC foam over other types are good resiliency, chemical resistance, and nonflammability. PUR foams have many things in their favor. They do not have undesirable bounce-back, they do not mat, stiffen, or crumble after long use or aging, they are nonallergenic, they are odorless, and they are unaffected by dampness. Moreover, since they are chemically inert, common cleaning chemicals, water, body acids, spilled foods, or liquids do not affect urethane foams.

Polyethylene (PE), polypropylene (PP), polystyrene (PS), polycarbonate (PC), and PUR are the most common foams; however, PP foams can provide favorable properties at a lower material cost. PP is stiffer than PE and can perform better in load bearing or structural applications. The low glass transition temperature of PP compared to PS provides increased flexibility and impact strength. Use of PP foams include packaging, automotive, insulation, and protection of underground pipe.

Structural foam is a term originally used for cellular TP articles with integral solid skins and possessing high strength-to-weight ratios (Table 8.4). Eventually the term covered high-density rigid cellular plastics strong enough for structural applications. As an example TS foams, such as polyurethane, are frequently referred to as structural foams. In general structural foams can be made from virtually any high-molecular-weight TP organic polymer and will have a cellular core and an integral skin on all sides. The skin is relatively non-porous in relation to the cellular core.

Table 8.4 Properties of ¼" thick thermoplastic structural foam (20% weight reduction)

Property	Unit	Method of Testing	High Density Polyethylene	ABS	Modified Polyphenylene Oxide	Polycarbonate	Thermoplastic Polyester	Polypropylene	High Impact Polystyrene	High Impact Polystyrene w/FR
Specific gravity	lbs./ft.³	ASTM-D-792	.60	.86	.85	.90	1.2	.67	.70	.85
Deflection temperature under load	°F@66 psi	ASTM-D-792	129.6	187	205	280	405	167	189	194
	°F@264 psi		93.5	172	180	260	340	112	176	187
Coefficient of thermal expansion	in./in./°F $\times 10^{-5}$	ASTM-D-696	12	4.9	3.8	2	4.5	5.2	9	4.5
Tensile strength	psi	ASTM-D-638	1,310	3,900	3,400	6,100	9,910	1,900	1,800	2,300
Tensile modulus	psi	ASTM-D-638		2,500,000	235,000	300,000	1,028,000	79,000	141,160	245,000
Flexural modulus	psi	ASTM-D-790	120,000	2,800,000	261,000	357,000	1,000,000	80,400	200,321	275,000
Compressive strength (10% deformation)	psi	ASTM-D-695	1,840	4,400	5,200	5,200	11,300	2,800	3,447	
Combustibility rating		UL Standard 94*		V-0	V-0/5V	V-0/5V	V-0	HB	HB	V-0

Structural-foam construction, when compared to an equivalent amount of conventional foam plastics, results in a 3- to 4-fold increase in rigidity. A broad and overlapping division of TPs exist between commodity and engineering groups of plastics used for structural foams. The commodity group consist of the styrenics (PSs, styrene-acrylonitriles, etc.), olefins (PPs, PEs, etc.) and vinyl chlorides (PVCs), while the engineering group includes acetals, ABSs, nylons, PCs, polyester and polyetherimide, plus various glass- or carbon-reinforced plastics.

The fairly dense varieties of TP and TS foams may be reinforced, usually with short glass fibers, but long fibers can also be used to provide increased performance (Chapter 15). The fibers are generally introduced into the basic ingredients and are blown along with them, to form part of, and to reinforce the walls of the cells. These plastic foamed composites are lightweight with high strength.

PC foam has outstanding impact strength, high heat resistance (deflection temperature of 280F (138C) at 66 psi (0.45 MPa), as well as very good flexural characteristics, creep resistance, and processability. PC is a good choice for structural components where load-bearing capability at elevated temperatures is a key requirement. It is an excellent alternative to metal for large components in the automotive, appliance, telecommunications, materials handling, and business machine industries. Foamable PC combines an unusual blend of rigidity, impact strength, and toughness with UL 94 V-0 and 5V flammability ratings.

Two principal PS foams that are fabricated are extruded foam and expanded for molded foams. PS foams are light, closed-cell foams with low thermal conductivities and excellent water resistance. They provide for low-temperature insulation and buoyancy media. The extruded PS foam is fabricated as billets and boards. They are made by extruding molten PS containing a blowing agent, under elevated temperature and pressure, into the atmosphere, where the mass expands. Billets and boards can be used directly or can be cut into many different forms.[254]

The foam sheet is clean, bright in appearance, has excellent cushioning properties, and is nonporous. The foam is extruded as a sheet and is subsequently vacuum thermoformed into the desired shapes for packaging, etc. (Chapters 5 and 7). Use includes low temperature insulation in freezers, coolers, and other types of refrigerated rooms; auto, truck bodies, and railroad cars; refrigerated pipelines; and low-temperature storage tanks for liquefied natural gas. They find usage as a replacement for molded-paper-pulp board in meat and produce trays and egg cartons.

Popular is roof-deck PS foam insulation where the foam is placed in the last hot bitumen layer of the roof, which is then covered with gravel or stone to hold it in place. Foam is used in the insulation of residential housing by using the foam in place of conventional sheathing. This type of foam when used in agriculture applications provides a means to insulate livestock buildings and low-temperature produce-storage buildings.

In the low-density range, 0.5 to 1.0 lb/ft^3, EPS (expandable PS) is used on boats as flotation, in packaging as an energy absorber, in building as insulation, and as a moisture barrier. In the middle-density range, from 1.0 to 4.0 lb/ft^3 the foam is used in packaging as a structural support as well as an energy absorber. Other applications include molding hot/cold drinking cups, in the construction field for such applications as concrete forms, in the foundry industry as mold patterns, as insulated containers of all sizes and shapes, and in materials-handling pallets. In the high-density range from 5.0 to 20.0 lb/ft^3 the foam exhibits almost wood-like properties. Such products as thread spools, tape cores, and furniture parts have been made from these foams.

Foams made from PVCs are of two types, open-cell and closed-cell. The open-cell foams are soft and flexible, while the closed-cell foams are predominantly rigid. Both types are made from plastisols, which are suspensions of finely divided plastics in a plasticizer (Chapter 16). The plastic does not dissolve appreciably in the plasticizer until elevated temperatures are used. Vinyl foaming methods are by using a CBA type or a mechanical frothing process in which a gas is also used as part of the blowing mechanism. In the preparation of a soft open-cell foam using a CBA the plastisol is first chosen for the characteristics desired. To the plastisol is added a paste made of powdered blowing agent dispersed in a plasticizer. One class of materials used for the large majority of vinyl foams is the azocarbonamides and other azo CBA compounds. They decompose at temperatures from about 250 to 425F (120 to 220C).

Soft, very flexible vinyl foams used for garment insulation, upholstery and similar applications are made by this CBA process. The more rigid foams used as underlays for rugs and flooring can also be made by this method, but require different plastics and lower plasticizer contents. Open-cell chemically blown vinyl foams generally have densities in the range of 5 to 30 lb/ft^3.

The open-cell vinyl foams produced by mechanical frothing, is used to produce sheets, such as flooring underlay, wall coverings, and other applications requiring relatively close thickness tolerances. Plastisol is mixed with a given amount of air in a high-shear, temperature-controlled mixing head (Chapter 12). The resulting product, resembling shaving cream, is cast onto a belt or fabric and knifed to a control thickness. Passage through an oven or heating tunnel then causes fusion of the plastisol.

Vinyl closed cell foams are made by the process used to produce open-cell CBA foams except that much higher pressures are used and the process is accomplished in two steps (preparing a hardened mix and going through a reheating process). The vinyl plastisol containing the blowing agent is first placed in a mold in which very little space is left for expansion. The mold is then heated, causing decomposition of the blowing agent and, at the same time, fusion of the foam. This step raises the internal pressure in the mold to anywhere from 200 to as much as 1600 psi (13.8 to 110 MPa). At these high pressures the gas is dissolved in the plastic in the form of microscopically small bubbles. It is cooled to produce a harden product.

The final action required is reheating the molded part at which time the plastic softens and the gas expands to form a closed-cell foam. With this technique it is possible to produce foams with densities as low as 2 lb/ft^3, although the usual range is 10 to 50 lb/ft^3. Because of this two-step procedure the process is much slower than the foaming procedure for open-cell foams. Close cell use includes athletic mats and marine flotation products.

Very popular for products such as metal and reinforced plastic laminates is crosslinked rigid vinyl with exceptional strength. It requires a combination of vinyl chloride polymer and monomer, plus maleic anhydride, isocyanate and catalyst. The components are poured into a heated pressurized mold. An exothermic reaction results in the maleic anhydride copolymerizing with the vinyl chloride monomer and grafting onto the PVC. Following molding the TP is exposed to hot water or steam, thereby causing the isocyanate to liberate CO that acts to expand the plastic mass. After expansion is completed the water then reacts with the grafted maleic anhydride, and the resultant maleic acid reacts with the isocyanate and crosslinks it.

PEs provide many unusual properties to the cellular plastics industry. These foams are tough, flexible and chemical and abrasion resistant. They are known to have superior electrical and thermal insulation properties. Their mechanical properties are intermediate between rigid and highly flexible foams. Densities are 2 lb/ft^3 and higher, approaching that of the solid plastics. The highly expanded polyolefin foams are potentially the least expensive of the cellular plastics. However, they require expensive processing techniques and for this reason their cost per unit volume is higher than that of low density polystyrene and polyurethane foams. Low density ranges of 2 to 10 lb/ft^3 are used for producing extruded planks, rounds, tubes, and special purpose profiles. Compression-molded items may also be produced from low density polyolefins. High density (10 to 40 lb/ft^3) polyolefins were used initially for electrical cable coatings. Low density polyolefin foams are being widely used in package cushioning. Energy absorption under continued impact provides protection for delicate electronic parts as well as heavy metal assemblies.

The production of cellular PE involves only one chemical reaction, the thermal decomposition of a blowing agent at a specific temperature, which action liberates an inert gas. The choice of blowing agent for electrical service applications is critical because of several unusual requirements. The gas from the blowing agent liberates gas. This residual by-product must not absorb moisture, which would adversely affect the electrical properties of the product. It is also important that the residue left by the blowing agent be nonpolar in order to avoid losses at high frequencies.

PE crosslinked foams offer higher stability and mechanical strength, better insulation characteristics, and improved energy-absorption properties. Most of these foams can be thermoformed, embossed, printed, laminated, or punched, using conventional equipment.

PP foam sheeting is specified in Federal Specification PP-C-1797. There are two types, Type I for general cushioning applications, and Type II for electrostatic protective cushioning applications. These foams are useful from –65F to 160F (–54C to 71C). The foam sheeting is intended for use as a protective cushioning wrap for low-density items. For high-density items it can be used for protection of surfaces from abrasion. PP foams in the structural foam field, supplanted HDPE foams. Their use continues to increase because of the extreme range of grades and properties available, plus a favorable price advantage, compared with other TP foams.[253] Glass-reinforced (30wt% chopped glass fiber) PP foams are commonly used. Low-density flexible PP foam film can be extruded in the 0.7 lb/ft^3 (11.2 kg/m^3) range.

Film sheeting consists of a uniform matrix of small closed-cell gas-filled bubbles. This film has outstanding toughness and strength over a wider range of temperatures and humidities. Its major characteristics, compared with other packaging films, are its light weight, resistance to tearing, chemical resistance, and moisture-barrier properties. Extrusion parameters are similar to those used for LDPE. A microcellular PP foam of this type has been used as a furniture wrap for use in packaging furniture in interstate commerce. The protective foam is wrapped around the item before insertion into a corrugated carton. Even with movement in the carton the PP wrap will stay with the item it is intended to protect.

The foam is non-dusting and non-linting. Typical packaging applications are surface protection for optical lenses, equipment with critical surfaces, electrical and electronic equipment, glassware, ceramics, and magnetic-tape rolls. There is microcellular PP foam sheeting that remains flexible and useful over the temperature range from −320F (−196C) to 250F (121C) (DuPont's Microfoam® sheet).

This foam tends to be more difficult to foam due to weak melt strength and low melt elasticity. Melt strength is the resistance of the melt to extension, while melt elasticity is a measure of elastic recovery. Melt strength and melt elasticity are directly related; the higher the melt elasticity, the higher the melt strength. With weak melt properties, cell walls separating gas bubbles in the foaming plastic are not strong enough to bear the extensional force as the gas expands, and they rupture. As a result, PP foam has a high open cell foam content, which is unsatisfactory for many applications. Melt strength is commonly increased by plastic modification, such as crosslinking or use of high injection pressures.

PUR continue to be important marketwise such as in the furniture and mattress business. They can be classified as flexible and rigid foams. In some cases, flexible foams can be further subdivided into flexible and semi-flexible (or semi-rigid) foams. Almost all mechanical and physical properties of rigid PUR foams depend on their foam densities. Flexible urethane foams with its open-cells have the property of complete recovery immediately after compression. They are classified as polyether foams and polyester foams. Polyether foams are further classified as conventional flexible foams, high-resilience flexible foams, cold-molded foams, super-soft foams, and viscoelastic foams. Microcellular flexible foams and integral-skin flexible foams are classified as elastomers. Different foams can be prepared by the proper choice of polyols. Polyisocyanates are used as joining agents for the polyols, and therefore, polyols are considered to be the major components important to determining the physical and mechanical properties of the resulting foams.[255, 256]

ABS foam provides properties that include impact, heat, and chemical resistance; low mold shrinkage rates; good long-term dimensional stability; and platability. Improved flammability characteristics are possible either by alloying (blending) with PVC or polycarbonate, or by compounding with halogenated additives. ABS compounds are slightly hygroscopic and should be dried prior to conventional injection molding to avoid splay marks (Chapter 2). High melt flow ABS grades display relatively stiff flow characteristics and, therefore, like all high-temperature TPs offer some resistance to foaming. ABS is susceptible to degradation and discoloration upon exposure to ultraviolet (UV) radiation. Modifying the flammability of ABS by means of halogen compounds significantly increases plastic cost and decreases color stability, especially in pastels, but to a lesser degree than with polystyrenes.

ABS structural foam can be processed by injection molding, through conventional or low pressure injection machines (Chapter 4); by expansion casting in rotational molding machines (Chapter 13) or conveyorized oven systems; or it can be extruded into profiles through conventional extruders (Chapter 5).

Even though most plastics can be made into foamed products, from a practical and market oriented view only a few different types are used. A few of these plastics will be reviewed. As an example limited use has been made using cellular cellulose acetate (CCA). The CCA was one of the first rigid foams produced and was used rather extensively during the 1940s and 1950s mainly in aircraft sandwich constructions.

Acetal translucent crystalline polymer is one of the stiffest TPs available. It provides excellent hardness and heat resistance, even in the presence of solvents and alkalies. Its low moisture sensitivity and good electrical properties permit direct competition with die-cast metal in a variety of applications. In addition, acetal has extremely high creep resistance and low permeability. Acetal is also available as a copolymer (Hoechst Celanese Corp.'s Celcon) for improved processability. The homopolymer (DuPont's Delrin) has a very low coefficient of friction and its resistance to abrasion is second only to nylon 6/6. Acetals are frequently blended with fibers such as glass or fluorocarbon to enhance stiffness and friction properties. Acetal is not particularly weather-resistant, but grades are available with UV stabilizers for improved outdoor performance. Acetal, whether homopolymer or copolymer, is not used to any significant degree in forming structural foams.

Ionomer foams are produced by extrusion or injection molding. Products are tough, closed-cell structures (6 to 9 lb/ft^3). The melt characteristics provide a tough skin in the low-density foam sheet and a better surface finish in the higher-density injection-molded products. The higher tensile strength and low melt point characteristics of an ionomer provide strong heat-seal seams for fabricated sections used in packaging applications. Products ranging from 3 to 30 lb/ft^3 are tougher and more solvent resistant than equal-density foams made from PE or PS. The ionomer-foamed sheeting may be vacuum-formed, laminated, stitched, glued, and modified for flame-retardant requirements.

Foamed PBT (polybutylene terephthalate) take advantage of the TPs UL 94 V-0 and 5V flammability rating, heat-deflection temperature of 420F (216C) at 66 psi (0.45 MPa), high flexural strength and modulus, and excellent chemical and solvent resistance. These translucent PBT plastics are especially suitable for applications requiring a combination of high heat endurance, stiffness, chemical resistance, and moderate creep.

In syntactic foams, instead of employing a blowing agent to form bubbles in the mass, preformed reinforcing bubbles of glass, ceramics, or plastic are embedded in a matrix of an unblown plastic. Use is made of microballoons or spheres ranging in diameter from 30 m to 0.0004 in. The matrix is with epoxy, polyester, phenolic, or urea plastic producing unique foam. This approach is to reduce weight. These high strength 8 to 50 lb/ft^3 foams are used as void fillers in boats, cores for aircraft sandwich structure, refrigerator cores, microwave absorbers, high frequency communication antennas, deep submergence vessels, preventing evaporation of liquids in tanks (oil, etc.), rocket bodies, etc.

A mixture of microspheres and the plastic can be formulated into a moldable mass that can then be shaped or pressed into cavities and molds much as molding sand and clay. The properties of the finished hardened or cured mass can then be tailored by a suitable plastic formulation. A mixture of TS polyester plastic and small hollow glass spheres, for example, can create synthetic wood.

Syntactic foam contains an orderly arrangement of hollow sphere fillers. They are usually glass microspheres approximately 100 microns (4 mils) in diameter, provide strong, impervious supports for otherwise weak, irregular voids. As a result, syntactic foam has attracted considerable attention both as a convenient and relatively lightweight buoyancy material and as a porous solid with excellent shock attenuating characteristics. The latter characteristic is achieved through crushing of the spheres and filling in the voids with plastic.

PROCESS

Based on production output, the most important processes are

1 extrusion (using PUR, PS, PE, PVC, CA, etc.),

2 cast expandable (PS, PE, PVC, PUR, phenolic, epoxy, PF, EP, SI, etc.),

3 spray (PUR, EP, UP, etc.),

4 froth (PLTR, PVC, UF, EP, etc.),

5 injection molding (PE, PP, PS, PVC, etc.),

6 compression (PE, PVC, UP, etc.),

7 sintering (PS, PE, PTFE),

8 leaching (PE, PVC, CA).

In use are equipment that operate hydraulically to all electrical and hybrid (hydraulically/electrically).

The processes are identified by different names with some overlapping. They include bead molding, calender foaming, extruder foaming, expandable plastic foam, expandable PS, expandable sheet stock, expandable PVC, extruded foam, injection-molded foam (low-, high-, and counter-pressure types), mechanical foaming, reaction injection molding, reticulated foam, spray foam, steam foam molding, structural foam, syntactic foam. Also the following, all starting with the word foamed: laminating, blow molding, casting, extruded film, frothing, gas counterpressure, injection molding, liquid, reservoir molding, and rubber. What follows is a review on the more popular foaming processes.

Extruding

Expandable beads (includes blowing agent with plastic) can be used but there are specific expandable plastic processes used that are relatively less expensive to use with more flexibility in handling. Extrusions of the more conventional TPs containing a chemical blowing agent are used. This material allows for a fairly simple operation on a normal single-screw extruder. The process is used where high densities of 0.3 to 0.6 g/cc. are acceptable; however, processors use as low a density as possible to save material costs.

The most used system is the direct gas extrusion process. It is possible to use the direct gas process with an extruder that does the melting of the plastic, mixing of the gas, cooling of the melt, and extrusion through the die. Both single- and twin-screw extruders are used. Although twin-screw extruders have the advantage of requiring less energy yet melting the plastic more efficiently than the single-screw, the limiting factor is the permissible internal pressure. High pressures require a very heavy bearing design in the extruder. The basic disadvantage of both systems is that they must melt, mix, and cool within a relatively short distance in an extruder with an L/D of, say, 30:1 (Chapters 3 and 5).

A tandem system specifically designed for foam processing separates these functions: the melting and mixing of the blowing agent is done in a primary extruder while the controlled cooling is done in a secondary extruder. Although slightly more expensive than the above described extrusion systems, the tandem extruder with its better overall economics and versatility, is the most commonly used.

Foamed sheet and film are manufactured by a tubular film-extrusion process using conventional methods with specially treated expandable pellets, or by injecting a propellant directly into a section of the extruder barrel with standard plastics and additives. In both techniques the extrudate passes through an annular tubing die and is expanded, either by blowing air inside the tube, or by drawing the tube over an internal sizing mandrel (Figure 8.1).

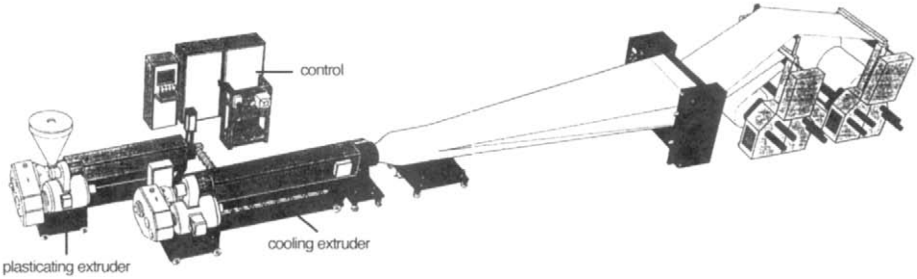


Figure 8.1 Example of tandem extruder foam sheet line (courtesy of Battenfeld Gloucester)

Die design is critical because in foam extrusion the viscosity of the melt is so high that imperfections from the screw or from the die flow are easily transmitted to the output product. To prevent this, the entrance to the die is designed to have a restrictive flow passage to help heal the melt as it comes off the screw flights and through spiders, and to provide for uniform flow into the die body (Chapter 17).

The die lips are the most important part of the die; at this point melt is being shaped, yet at the same time is prevented from foaming inside the die. The die lips are interchangeable so that with any type die body a range of die lip sizes can be used in order to change the blowup ratio, just as the sheet, etc. emerges from the die lips the stretching and orienting take place.

Applications for these foamed products are many. An example is meat trays that are normally produced from PS foamed sheet with a thickness of approximately 0.095 in. and a density of about 5 lb/ft^3. These trays are manufactured with little skin. The meat should not stick to the plastic when frozen, nor should the meat juice penetrate into the tray, and the tray should not break when handled. Strength is achieved by correctly orienting the sheet resulting in cells that are round from a plan view. The cell size, which is determined by the amount and type of nucleating agent, is kept fairly fine to give the trays a soft, glossy appearance.

Where deeper draws are required, the material has to be stiffer with coarser cells. Typical are egg cartons and flats used in bulb shipping. PS sheet for trays or cartons are about 0.080 to 0.095 in. thick and the density varies between 6.9 and 8.1 lb/ft^3. On one side of the sheet, by use of the proper air ring (Chapter 5), a strong skin is formed, improving product appearance and allowing for better thermoforming.

Continuing with properly providing foamed products to meet their performance requirements are food trays, such as those for apples or pears. They are designed to protect the fruit under all conditions of shipping and must hold the weight of the produce. Therefore, a high degree or orientation is put into the sheet providing for more flexible cells. Sheet thickness is approximately 0.080 in. and density is about 6.25 lb/ft^3. Trays are manufactured without skin to present a soft, cushion surface to the produce, and to prevent cracking.

Different packaging requirements exist in the fast-food industry. Stackability, appearance, insulation, and a surface that lends itself to good printing are best seen in hamburger packs. Light skins on both sides provide a glossy appearance and allow for easy printing. Other products have their specific requirements. They include many products such as institutional feeding trays, automotive headliners that are based on foam cores, dielectric material for insulating the center wire of coaxial cable from the sheath, packaging to protect fragile electronic equipment, dishware, etc.

The most popular materials are styrenics and olefins, and engineering plastics such as modified polyphenylene ether or polycarbonate (Chapter 2). Fillers for enhanced physical properties, UV stabilizers, and flame retardants are common additives.

Casting

Foamed casting is a simple non-mechanical version of pouring (Chapter 11), reaction injection molding (RIM) (Chapter 12) or liquid injection molding (LIM) (Chapter 16). Liquid components of the plastic with suitable additives are mixed and poured into an open mold (Chapter 11). Polymerization and foaming take place in the mold cavity, which could include a matching mold cavity to enclose the foaming action. Molds are generally heated or oven-cured, sometimes both.

Spraying

Spray techniques are used for filling molds and panels and for applying foam to plane surfaces (Chapter 16). Spraying is particularly useful in applications where large areas are involved, such as tanks or building walls. Spraying is the simplest and least expensive way to produce TP urethane (and other) plastic foams. In addition, spraying equipment is reasonably priced and portable. Foam can be applied without molds or jigs of any kind. In spray applications the ingredient mixing is accomplished by atomization of the materials as they leave the nozzle of the spray gun. When necessary, heat may be applied to the polymer to reduce the viscosity to the desired level.

The rise time for airless-sprayed urethane foam is about 30 s. It can be refoamed for additional thickness after this period. The foam can be walked on after 3 to 4 minutes and reaches its full properties in 24 h. The airless spray gun is held about 30 in. (76 cm) from the surface and moved steadily over it. Dispensing rates of 4 to 6 lb (1.8 to 3.6 kg) per minute are generally considered optimum for most spray applications. The surface on which the foam is sprayed must be free of loose scale or grease. The adhesion of urethane foam to steel is essentially equal to the tensile strength of the foam, provided the surface is clean. Aluminum surfaces, on the other hand, do not provide a good bond unless a primer coat, such as vinyl wash, is used prior to spray foaming.

A non-burning barrier approved by the appropriate building codes must protect spray-applied urethane foam in buildings. Without such barriers polyurethane foam will spread fire rapidly once ignited, even with fire-retardant grades. With few exceptions, all model codes require that foam plastic insulation be covered by a thermal barrier equal in resistance to ½ in. (1.27 cm) gypsum board, or be used only in sprinkler buildings. The gypsum board or equivalent is supposed to prevent the foam from reaching a temperature of 325F (163C) for a 15-minute period when subjected to the ASTM E 119 time-temperature curve, which averages 1100F (593C).

Frothing

DuPont introduced this urethane process in 1961 that operates in a two-stage expansion system. The main idea is to introduce into the

PUR formulation another more volatile liquid. With this approach instead of delivering a liquid blend into a cavity for foaming, a pre-expanded one is delivered. In this manner a froth stream of 8 to 12 lb/ft^3 (128 to 192 kg/m^3) density is poured into a cavity where it completes its expansion to a low density of 1.5 to 2.5 lb/ft^3 (24 to 40 kg/m^3), which is the density range desired. In the froth stage the stream is quite fluid, resembling shaving cream in appearance, and flows readily. Frothing is particularly suited for void filling or panel manufacture. Advantages of this process are:

1 lower mold pressures during foaming,

2 lower and more uniform foam densities,

3 lower densities obtainable with low-temperature molding,

4 ability to lay down expanding foam without causing its collapse or density change, and

5 froth may be leveled by methods similar to those used with concrete in the construction industry.

Frothing of the urethane foam-component mix occurs when the volatile liquid is vaporized by a reduction in pressure as the material is discharged from the mixer. By employing a combination of fluorocarbons of different boiling points a two-stage expansion is possible. The vaporization of the low-boiling solvent occurs in the initial stage, with the final foam density resulting from the supplemental expansion of the higher-boiling solvent due to the heat generated by the reactions between the hydroxyl- and isocyanate-containing foam components. With conventional molding techniques the foam must expand 30 to 40 times in the mold to reach its final volume. While in the frothing process the final expansion in the mold is reduced to only 3 to 6 times the froth volume.

Expandable Plastic

Different plastics are used with foamed PS or expandable polystyrene (EPS) being the most popular. Expandable plastic foams illustrate the use of plastic concentrates that include the blowing agents. Plastic beads containing the blowing agent are supplied to the molder as accurately formed solid spheres. The beads may be about 0.1 to 0.2 mm in diameter and they contain a blowing agent, usually pentane. This process is also called bead molding or steam molding, but the most popular name is expandable EPS. Other plastics are foamed by the same or similar methods, with EPS produced in the largest quantities.

The process involves two major steps. As shown in Figure 8.2 the first step consists of preexpansion of the virgin beads by heat (usually steam, but also used are hot air, radiant heat, or hot water). Steam is extensively used because it is the most practical, most economical, and has other advantages. The preexpansion step brings the beads almost to the required density within the molded product, then they are stored for 6 to 12 h to allow them to reach an equilibrium.

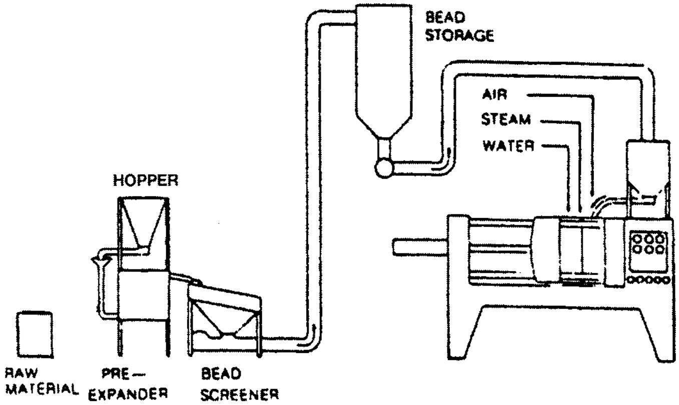


Figure 8.2 Expandable polystyrene process line starts with preexpanding the PS beads

Different preexpansion equipment and controls are available; each type has advantages and disadvantages. The type of expander and controls will depend on the production quantity. There are continuous, single-stage, multistage, and discontinuous preexpansion systems. As an example of performance, consider the advantages of the continuous system over the other types: lower unit cost, higher throughput, easier maintenance, and greater reliability. Its principal disadvantage is the time it takes to change between materials of different bulk density. This disadvantage is avoided with the discontinuous unit.

The next step conveys these beads, usually by air through a transport tube, to a two-cavity mold. If problems exist in having the beads properly fill the cavities, a vibratory against the mold will have the beads relocated so that they fit snuggly to each other. Final expansion occurs in the mold, usually with steam heat, either by having live steam going through perforations in the mold itself (Figure 8.3) or by steam probes that are withdrawn as the beads are expanding. During expansion the beads melt together, adhering to each other and forming a relatively smooth skin, filling the cavity or cavities. Multiple cavities can be used with small parts.

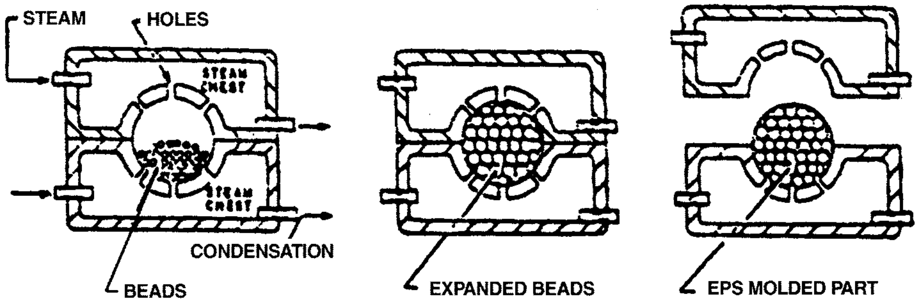


Figure 8.3 View of PS beads in a perforated mold cavity that are expanding when subjected to steam heat

The heat cycle is followed by the cooling cycle. Because EPS is an excellent thermal insulator, it takes a relatively long time to remove the heat before demolding. If the heat was to remain, the product would distort. Cooling is usually by water spray over the mold. To facilitate removal, particularly for complex shapes mold release agents are used. The final density is about 0.7 to 10 lb/ft^3 (11 to 160 kg/m^3) or in normal molding the density of the product will closely approximate the bulk density of the unheated beads.

EPS molds have double walls; the inner wall is the actual shape to be formed. It is perforated with vents to allow steam to penetrate the foam; the hot gases that develop leave the product through these vents. Thus, the double walls allow for encasing the steam that is delivered to the mold and in turn flows throw the vents. Before removal from the mold, products are stabilized by creating a vacuum and spraying water on the inner mold wall, causing diffusion of gasses from the many cells as well as a reduction in temperature.

EPS molding generates pressures of less than 30 psi (2 kPa) in most mold applications. This low pressure allows the use of inexpensive molds such as aluminum. To process the other expandable plastic foams (EPFs), such as PE, PP, and PMMA, the equipment for EPS can be used with only slight modifications.

Pentane has been used as a gas-blowing agent to produce different foamed plastics or elastomers, particularly in EPS. Pentane is used to produce certain rigid polyurethane insulation foams as an alternate to the past used CFC blowing agents. As an example during PUR processing, it can be added separately to the mixture bypassing on the high pressure side of the mixing head, thereby bypassing explosive-proof mix chamber and polyol metering pump. Because of pentane's flammability and chemical makeup, no problems exist when properly processed. It is halogen-free, non-polar, and accepted as non-toxic. The flammability of foam products can be controlled through proper use of flame-retardants. It is a hydrocarbon in the methane series occurring in petroleum.

Expandable polyethylene (EPE) is a low-density, semi-rigid, closed-cell, weather-stable PE homopolymer that is easier to compress than EPS but less compliant than flexible PUR. EPE foam follows a similar processing technique as that of EPS starting with the use PE beads. Conventional EPS molding presses can process EPE with the addition of a modified filling device, provision for higher molding pressure, and postmold oven curing. Their density range is 1.8 to 7.5 lb/ft^3 (29 to 120 kg/m^3). The most commonly used density is 1.8 lb/ft^3 (29 kg/m^3).

Expanded polyethylene copolymer (EPC) is a 50/50 wt% of polyethylene and polystyrene. Combining the properties of both plastics widens the selection of resilient materials for packaging engineers. EPC is a material that falls between EPS and EPE in performance, but exceeds both materials in toughness. The tensile and puncture resistance of EPC is superior to all of the moldable resilient foams available. It has good multiple-impact performance characteristics with better memory than EPS, but not as good as EPE. The cushion performance of EPC parallels EPE but at higher levels even after repeated drops. EPC is especially good for reusable material-handling trays and packaging applications that require a nonabrasive, solvent-resistant, impact absorbing material with a superior toughness that elongates, compresses, and flexes without material fatigue.

EPC is a low density, semi-rigid, closed-cell material that requires refrigerated storage below 40F (4.4C) in its raw granular form and has a shelf life of at least one month. The material expansion and conveying of the sensitive pre-puff requires special handling and molding within a short period of time. The molding process and equipment are similar to EPS, but with slower molding cycles.

Expandable styrene-acrylonitrile (ESAN) is a moldable, lightweight, semi-rigid, closed-cell, highly resilient plastic foam. The raw materials can be stored without refrigeration and they have a shelf life of about 6 months provided some simple precautions are observed as provided by the material supplier. Processing is similar to EPS except that it has extended fabricating cycles due to the higher level of blowing agent. Postmold oven curing is not necessary. A low density of more than 40 times expansion can be reached during the preexpanding phase, as low as 1.0 lb/ft^3 (16 kg/rn^3) on the first pass through the expander and 0.8 lb/ft^3 (13 kg/m^3) on the second pass.

Molding

Foam molding operations are those in which a liquid mixture of foam components is used. It is poured into a mold cavity to form a cellular shaped product. The molded product is later removed after setting or curing. As reviewed in the case of expandable polystyrene beads the preexpanded or virgin beads are poured into a mold and heated to form the desired object. In this case, liquids are not used, although the free-flowing beads might be considered a fluid.

A number of flexible foam components are molded, rather than fabricated from slabstock. For a production quantity of intricately shaped products, molding results in savings up to 15%, compared to slabstock with secondary operations (Chapter 18). Rigid foam can also be molded, although such applications are fewer in number. In a typical low pressure molding operation a mold is preheated and coated with a mold release agent. A preheated amount of liquid mix is poured into the mold, the mold is closed and the ingredients foamed to the mold cavity configuration. After curing and cooling, the part is stripped from the mold. Scrap rate could be from zero to up to 5 wt% depending on mold design. Mold temperatures for commodity plastics are usually in the range of 150 to 160F (66 to 71C). The best results are usually obtained when the mold release agent is spray-applied to the clean, warm mold just before each pour. Care must be taken, however, to remove all solvents from the mold release compound before the foam components are poured into the mold cavity.

Curing of the molded TS polyurethane foam product is usually carried out in two stages, a precure of 15 to 20 minutes of about 270F (132C), permitting removal of the part from the mold, and a final cure of 60 minutes at the same temperature. Mold release of polyurethane foams can be difficult since uncured polyurethane has well-known adhesive properties. Two basic types of mold release agent are used. The first requires the hot molding to be stripped from the mold. Mixtures of paraffin and microcrystalline waxes are used for this technique, in which hot wax releases the part from the mold. The molds must be heated and coated with wax before each filling. There is a tendency, however, for the paraffin wax to be slowly oxidized by the repeated heating. For this reason a release agent containing an antioxidant should be used. The breakdown products formed have no release properties, and it is important to use a thin layer of wax each time a molding procedure is carried out.

A release agent, such as polyethylene waxes, is used if the mold must be stripped away when cold. In this case the foam comes away from the release agent. Mold release problems can be reduced by adding small amounts of dibutyl tin dilaurate, which promotes curing at the surface of the mold and thus improves mold release.

Slabstock molding requires very little curing. A bank of infrared heaters suspended above the conveyor is often sufficient to facilitate curing. In conventional molding, however, the exotherm generated is not sufficient to cure the foam, and external heat must be applied. Microwave curing permits a reduction in curing time from 20 to 4 minutes. Plastic molds are used with a gel coat of epoxy resin containing iron powder. The plastic molds must be cooled to an even temperature before refilling. There is evidence to suggest that foam cured with microwaves have properties slightly superior to foam cured by conventional heating, especially in compression set. Dielectric heating has also been developed for use in curing.

Injection Molding

The conventional and slightly modified injection molding machines (IMMs) are used to produce different types of foams (Chapter 4).

Low pressure or short-shot conventional foam IM (injection molding) processing methods are the most commonly used because they are easy, simple, and best suited to economical production, particularly of large, complex, 3-D products. A controlled melt mixture (plastic and blowing agent) is injected into a mold cavity from the IM plasticator (Chapter 3) creating a low cavity pressure usually 1.4 to 3.5 MPa (200 to 500 psi). As shown in Figure 8.4 two steps occur using a reciprocating IMM. First the plastic melt with blowing agent (nitrogen, carbon dioxide, or hydrocarbon gas) is directed into an accumulator. The next step has the accumulator very quickly deliver the hot plastic mix into the mold cavity. Also used are two-stage IMMs (Chapter 4).

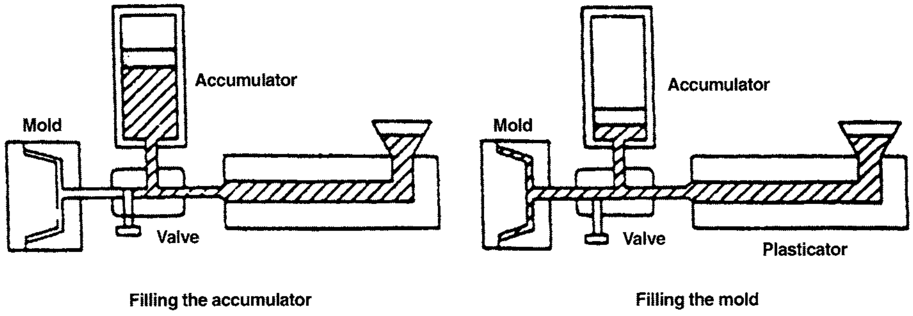


Figure 8.4 Schematic of foam reciprocating injection molding machine for low pressure

Along with about 0.5wt% of CBA, this mixture can be injected directly from the barrel of a conventional injection molding machine (with limited modifications) or via an accumulator (two-stage IMM). The mixture only partially fills the mold (short shot), and the gas bubbles, having been at higher pressure, expand immediately and fill the cavity. As the cells collapse against the mold surface, a relatively solid skin of melt is formed over the rigid foam core. Skin thickness is controlled by the amount of melt injected, mold temperature, type and amount of blowing agent, temperature and pressure of the melt, and capabilities of the molding machine, particularly its speed of injection.

There is low pressure with coinjection. This technique involves the usual separate injection of two compatible plastics that are coinjected using two injection plasticators (Chapter 4). A solid plastic is injected from one plasticator to form a solid, smooth skin against the surfaces of the mold cavity. Simultaneously a second material, a measured short shot containing a blowing agent, is injected to form the foamed core. This approach can also take a relatively full core shot and have the mold open [as in injection-compression molding (Chapter 4)] after the skin solidifies, having the melted core expand with mold-opening action.

There is low pressure with surface finish in low-pressure surface-finish (LPSF) molding, not using coinjection or injection-compression molding (Chapter 4), the volume of the molding cavity is always larger than the volume of the plastic in the unfoamed state. The low pressure allows microbubbles to nucleate and grow. Foam expansion occurs during filling, and growing bubbles are carried to the mold surface, creating unacceptable surface irregularities and imperfections called splay or swirl pattern. The irregularities can be seen and felt; the surface roughness can be as much as 1000 μin. (25 μm). Products needing smooth, finished surfaces require secondary operations, usually sanding, filling, and painting.

There are techniques to improve surface appearance during fabrication. The principal process variables are melt and mold temperatures, injection rate, the nature or type of blowing agent, and its concentration. Cyclic heating and cooling of the mold surface and direct injection of blowing agent into the melt as it is being injected into the mold are two of the methods used.

The gas counterpressure IM method uses a sealed mold pressurized to 2.8 to 3.5 MPa (400 to 500 psi) with an inert gas, sufficient pressure to suppress foaming as the plastic mix enters the mold cavity. After the measured shot is injected, the mold pressure is released, allowing the instantaneous foaming to form the core between the already formed solid skins [Figure 8.5(a)]. The mold action is similar to injection-compression molding. Another technique is gas injection molding, used to develop similar foamed structures. Once the plastic at the mold surface has solidified, the gas pressure is released to permit the remaining melt mix to foam, creating the product's core.

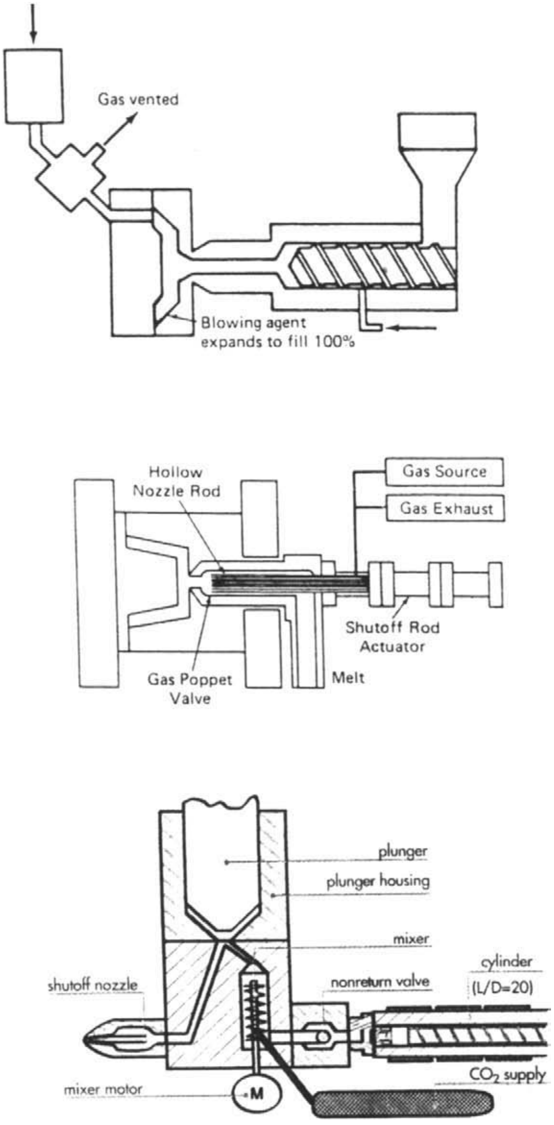

Gas vented
Blowing agent expands to fill 100%
Hollow Nozzle Rod
Gas Source
Gas Exhaust
Shutoff Rod Actuator
Gas Poppet Valve
Melt
plunger
plunger housing
mixer
cylinder
(L/D=20)
shutoff nozzle
nonreturn valve
CO2 supply
mixer motor
M

Figure 8.5 (a) Schematic of gas counterpressure foam injection molding (Cashiers Structural Foam patent)
(b) Example of an IMM modified nozzle that handles simultaneously the melt and gas.
(c) Microcellular foaming system directing the melt-gas through its shutoff nozzle into the mold cavity

There are different gas operating patented foam IMM systems. Examples are shown in Figures 8.5(b) and 8.5(c). The Figure 8.5(b) is a Hoover/ Carbide patent. Figure 8.5(c) is the patented Demag Ergotech process for molding microcellular foam products.[247] Liquid CO_2 enters the melt downstream of a conventional or two-stage IMM plasticator (Chapter 3). There is Trexel Inc., Woburn, MA a licensor of the MuCell microcellular foam IMM or extruder process. It injects CO_2 or N_2 into the IMM plasticator. There exists a licensing agreement between Trexel and Demag Ergotech.

The high pressure molding system that uses an expandable mold is a takeoff of conventional IM (Chapter 4). It starts by injecting the heated melt mix (with blowing agent) into the mold, creating a cavity pressure higher than the blowing-agent gas pressure (usually much higher). This action is to ensure no loss in gas pressure during injection. Pressure for certain machines could be 5,000 to 20,000 psi (34.5 to 138 MPa). With the mold being entirely filled the melt next to the cavity wall forms a solid skin as it starts solidifying against the mold surfaces. As soon as the skin surface hardens to a desired thickness, a second step occurs where the cavity mold opens reducing the pressure allowing the remaining melt to foam between the skins. The opening occurs whereby the male plug retracts but remains within the female cavity as in injection molding (Chapter 4).

The mold can be modified to meet certain different shapes. The molding can be made either by withdrawing cores or by special press motions that partially open the mold halves (such as the compression molds used in coining to provide 2-D action; 3-D mold actions are also used). The degree of foam density, wall thickness, and surface finish depends on the foam mixture (constituents and amounts). The machine controls the time cycle and the mold action required.

Structural-web molding is a low pressure foam molding method. It is the phrase usually used to identify the gap between structural foam (SF) molding and injection molding. Its surface does not have the usual SF characteristic swirl pattern. It can produce very large, lightweight parts with smooth surfaces like conventional injection molded parts.

Reaction injection molding (RIM) includes fabricating rigid, flexible microcellular, and rigid microcellular polyurethane foams. The process embodies high-pressure-impingement mixing of the liquid components before they are injected into the mold. RIM has advantages over the standard low-pressure mechanical-mixing systems in that larger parts are possible, mold cycles are shorter, there is no need for solvent-cleaning cycles, surface finishes are improved, and rapid injection into the mold is possible (Chapter 12).

Liquid injection molding (LIM) is a variation of the RIM process. The major difference is in the manner in which the liquid components are mixed. In the LIM process the entire shot is mixed in a chamber before injection into the mold, rather than being continuously mixed and injected, as in the RIM process (Chapter 16).

Structural Foam

Different plastics are used such as PSs and PVCs to produce building trim and moldings, picture frames, etc. The most important structural foam molding processes have been reviewed. They are the low and high pressure injection molding processes. Structural foams with solid skins and cellular cores are extruded in the form of profiles, pipes, tubes, sheet, etc. using conventional extruders that include handling the blowing agents. As reviewed with IMMs the blowing agents can be mixed with the plastic as it enters the hopper, enters the screw plasticator melt, or use a mixing device to mix the melt with the blowing agent.

Foam Reservoir Molding

Foamed reservoir molding is also known as elastic reservoir molding. It has had limited use. This process creates a sandwich of plastic-impregnated, open-celled, flexible plastic foam between the face layers such as fibrous reinforcements. When this plastic composite is placed in a heated mold and squeezed, the foam is compressed, forcing the plastic and air outward and into the reinforcement. The elastic foam exerts sufficient pressure to force the plastic-impregnated reinforcement into contact with the mold surface and simultaneously removing entrapped air.

Polyurethane Process

When processing PURs different processing techniques are used. The specific processes include free-rise, liquid (pour-in-place), froth, and spray foaming techniques. When injected, there is the common injection molding process and others. When the PUR liquid ingredients are mixed, gases are produced which cause the mass to expand as it stiffens and hardens. The reaction is complete in a few minutes. Figure 8.6 shows different process systems (top/liquid, center/froth/ bottom/spray) where in each case the blowing agent can be added to either or both components A and B.

In a sandwich structure the liquid mix is poured between the cover sheets and foams between them, bonding directly to the sheets without

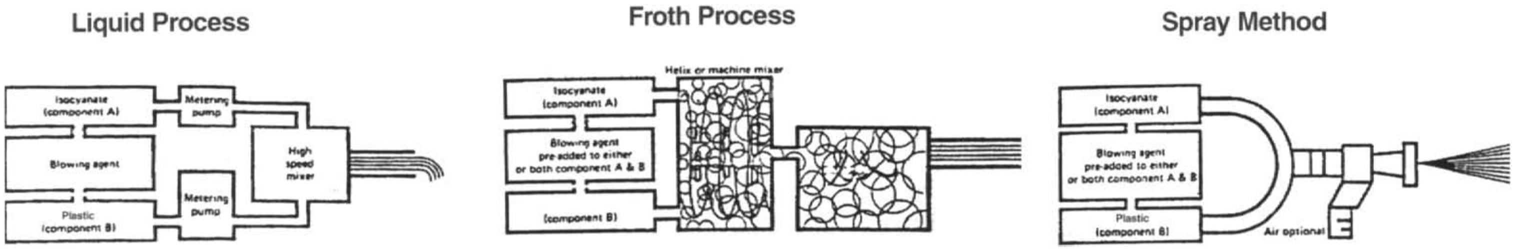

Liquid Process
Isocyanate (component A)
Blowing agent
Plastic (component B)
Metering pump
Metering pump
High speed mixer
Froth Process
Helix or machine mixer
Isocyanate (component A)
Blowing agent pre-added to either or both component A & B
(component B)
Spray Method
Isocyanate (component A)
Blowing agent pre-added to either or both component A & B
Plastic (component B)
Air optional

Figure 8.6 Liquid (liquid), froth (center), and spray polyurethane foaming processes

an adhesive. As foamed-in-place materials expand, they can exert appreciable pressure, so the sandwich sheets have to be held in a rigid frame to prevent bulging until the reaction is complete. To overcome this pressure, the liquid mix may be allowed to form a froth of almost its ultimate volume prior to pouring. The result is little or no pressure and rigid foam.

Flexible PUR foam, such as that used in upholstery, is made by continuous deposition on a belt before being cut into blocks or sheets of desired shape and size. Other foam materials may be handled in somewhat similar ways, and may be pre-foamed or foamed-in-place.

Water is the component-forming blowing gas in the formulation for PUR soft, flexible foam; it forms carbon dioxide with isocyanates. The evolution of heat and the change in temperature caused by this gas-generating reaction mean that other blowing agents (such as dichloromethane) have to be used, along with coolants, in order to produce low-density foam of less than 20 kg/m^3 (Figure 8.7).

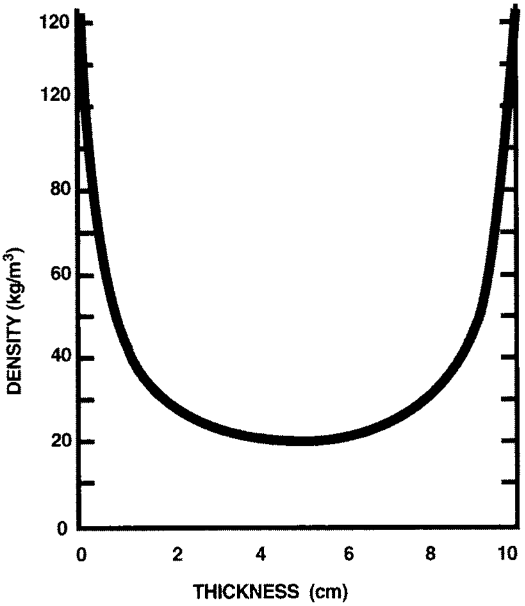


Figure 8.7 Example of flexible foam density profile

A rigid, foamed crosslinked PUR, usually with closed cells, is formed by the reaction of a diisocyanate and often methane diisocyanate (MDI) or polymeric MDI with polyester or more usually with a polyether polyol. Foaming may result from the water, which reacts with isocyanate groups to form carbon dioxide but is usually the result of using other blowing agents, sometimes in combination with water. They are more rigid than flexible foams because they contain more crosslinks. This is accomplished by the use of polyols, usually polyoxypropylene glycols of low molecular weight, which are highly branched by mixing of higher functionality comonomers (such as sorbitol or pentaerythritol).

9 CALENDERING

Introduction

This process is used to convert thermoplastic materials into continuous sheets, films, and for applying plastic coatings to textiles, paper, or other supporting material. When coating the calendering line is also called a coating machine. Calendering is an alternative to extrusion with the usual film at three or more mils (75 microns) thick (Chapter 5). For the production of sheet or film plastic melt is compounded and pressed as it passes through the nips of a series of three or more heated highly polished steel rolls.

A plastic bank is formed into a web in the nip between the first pair of rolls. Passing through the second and third nips further reduces the thickness. Final thickness of the sheet is determined by the gap between the last pair of rolls called the gauging rolls. Finally, a take-off roll pulls the hot sheet around a chilled roll to cool the sheet or film web (Figure 9.1). In this industry bank is identified as the quantity of plastic present in the nip formed between two rolls (Figure 9.1). [Bank marks are surface roughness on sheet caused by incorrect temperature or sizes of banks. They can be minimized by optimizing formulations, calendering speeds, and roll temperatures so as to obtain the most orderly behavior of the rolling banks of stock at the calender-nip entrances.]

Calendering converts plastic into a melt and then passes the pastelike melt through roll nips of a series of heated and corotating speed-controlled rolls into webs of specific thickness and width. The web may be polished or embossed, either rigid or flexible. Proper calendering requires precise control of the complete roll temperatures, pressures, and speed of rotations. An embossed design can be produced on the surface by using an engraved roll, calendering a mixture of granular

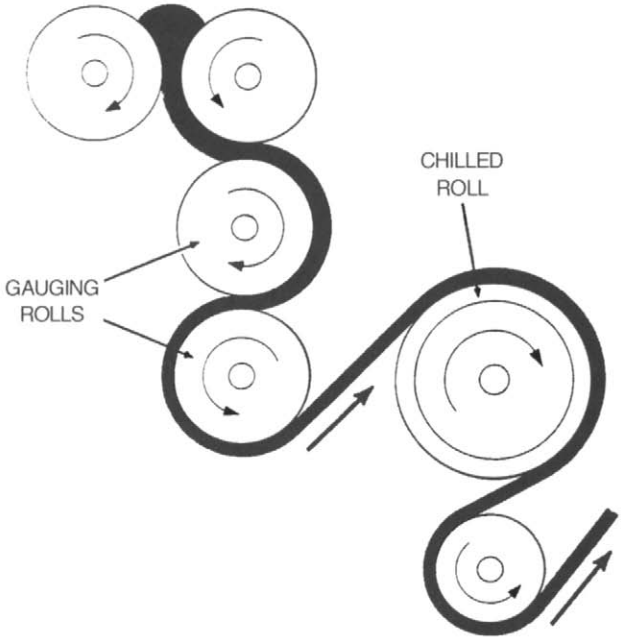


Figure 9.1 Example of the sheet or film passing through nip rolls to decrease thickness

plastic chips of varying color may produce unusual decorative effects such as marblization, and so forth. Calendering often processes vinyl plastics.

The complete equipment usually consists of a mixer such as a Banbury mixer followed by the heated rolls, chilled rolls, and finally a windup roll.[3] The windup roll controls the tension on the film or sheeting as it moves through the calender rolls. Calenders are generally designed to meet the specific needs of the customer. Once installed and operating continuously, the cost per pound of film or sheet is lower than by any other process such as extrusion.

The capital cost for a calendering line will average at least $10 million. A line, probably the largest in the world processing PVC sheet was build by Kleinewefers Kunststoffanlagen GmbH, Munich, Germany. Cost for this 5 roll L-type configuration was $33 million (1999). It has 3,500 mm roll-face widths and 770 mm diameters with an output rate at 4,000 kg/h.

Plastics that melt to a rather low viscosity are not suitable for calendering. Additives can have a major influence on processability. With this understanding comes the ability to make calenders more productive by increasing their speed. They also produce films and sheets with tighter thickness tolerances and improved uniformity and can handle thicker sheets more effectively.

Equipment

The purpose for the calender is to provide sufficient energy to convert a mass of plastic into film or sheet form without supplying so much heat as to cause degradation. This is a very important consideration particularly when processing rigid PVC. Variations in these multi-million dollar calender lines are dictated by the very high forces exerted on the rolls to compress the plastic melt into thin film or sheet web constructions. Important is the complete removal of any metal or hard surface material. This includes microscopic particles. As an example a micron size piece of metal or slight scratch will destroy the rolls, etc. Replacing these very expensive very heavy rolls is expensive. This type of equipment may not be in the storeroom. From the start to the end of the calendering process extreme care has to be taken to ensure there is no contamination of the equipment or plastic being processed. Preventative maintenance of these lines is a continuous operation that includes the operating environment in the plant to be a relatively clean room.

Calenders vary in respect to the number of rolls and their arrangements. Examples of the layout of the rolls are the true L, conventional inverted L, reverse fed inverted L, 1, Z, and so on. These large diameter heated rolls have the function to convert the high viscosity plastic melt into film or sheet. Figures 9.2 and 9.3 provide examples of lines.

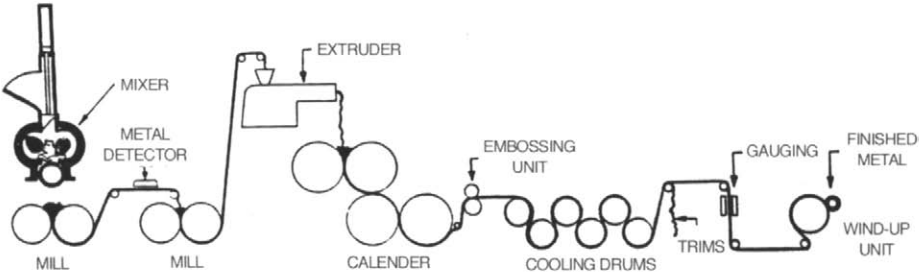


Figure 9.2 Calender line starting with mixer

In the early days of calendering plastics three-roll vertical rubber machines were used. Problems developed in processing plastics. They

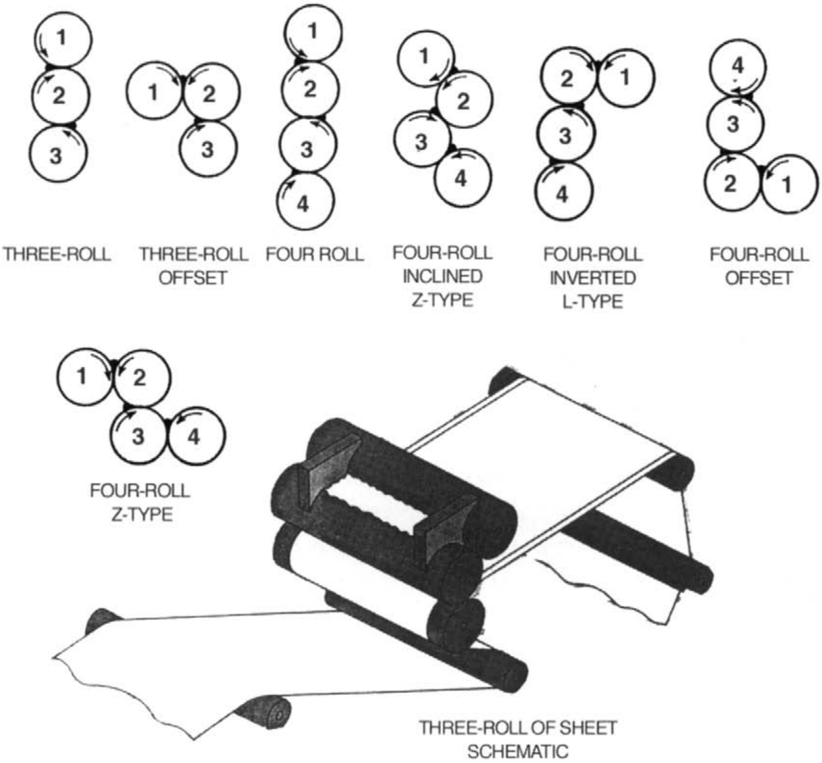

1
2
3
THREE-ROLL
1
2
3
THREE-ROLL OFFSET
1
2
3
4
FOUR ROLL
1
2
3
4
FOUR-ROLL INCLINED Z-TYPE
2
1
3
4
FOUR-ROLL INVERTED L-TYPE
4
3
2
1
FOUR-ROLL OFFSET
1
2
3
4
FOUR-ROLL Z-TYPE
THREE-ROLL OF SHEET SCHEMATIC

Figure 9.3 Examples of the arrangements of rolls in a calender line

included difficulty in feeding horizontal nip, gauge variations, temperature variations due to using cored rolls, no capability for cross-axis or roll bending adjustments, and roll floating due to pressure variations in the feed nips. As time passed these problems were continually reduced or eliminated particularly on the smaller calenders. The offset rolls were designed to eliminate the major difficulty of the horizontal feed nip. Because the material drops by gravity into the vertical pass, the offset feed nip provides important savings in manpower and yield. Also, the pressure fluctuations of the feed to the other nips are minimized because roll No. 2 will tend to float horizontally rather than vertically in relation to roll No. 3 (Figure 9.3). To reduce gauge variation in this setup fitting roller bearings can stabilize roll No. 3 floating roll. Cross-axis and/or roll bending may be fitted to roll No. 3 or roll No. 4. With this compact setup it is still easily accessible for starting up and operating the machine.

The Z-type roll arrangements followed developments in offset rolls. This design eliminated the floating No. 3 roll on a calender fitted with bearings. Each roll can be preloaded on to its bearings at a point that is the resultant of the material pressures and the roll weight. This approach had other advantages that included reduction of the height required for the installation of rolls. In turn plant space requirement was reduced along with reduced building cost. Its disadvantage is limiting the ease of access to roll No. 2 or No. 3 in the case of the inverted Z. With the inclined Z it is more difficult to feed than a standard type Z because the nip does not hold as much material.

Calenders with at least four to six rolls are used to fabricate thin rigid sheet where the extra nips greatly improve the surface finish of the sheet. The more popular are the four-roll inverted L calender and Z calender. The Z calender has the advantage of lower heat loss in the film or sheet because of the melts shorter travel and the machines' simpler construction. They are simpler to construct because they need less compensation for roll bending. This compensation occurs because there are no more than two rolls in any vertical direction as opposed to three rolls in a four roll inverted L type calender. The speed of the calendering rolls usually differs. They operate at different speeds to provide the best performance of the melt, particularly the required shearing action (Chapter 1).

High pressures of at least up to 6,000 psi (40 MPa) can bend or deflect the rolls. This calender bowl deflection is the distortion suffered by calender rolls resulting from the pressure of the plastic running between them. If not corrected, the deflection produces film or sheets thicker in the middle than at the edges. The amount of thrust exerted by the material depends on processing factors such as method of feeding stock into the calender, plastic temperature, melt flow behavior (Chapter 1), required thickness and width, and speed of the calendering line. Unfortunately the rolls do not bend like a simple beam that is freely supported at each end and uniformly loaded along its length. Each calender roll varies in thickness between the face and its journal. Because it rotates the pressure distribution across the roll is not exactly equal. Thus it does not deflect on conformation with the classical engineering equation[1] but in such a manner simulating a profile of a U-shaped frame forming a collar about an ox's neck resembling an oxbow.

In order to compensate for this thickness variation requires the surface of the roll to fit a certain profile (crown). The amount of crown, that is the difference in roll section radius between ends and center, will vary depending on the rheological properties of the plastic being processed (Chapter 1). Rolls are crowned resulting in having a greater diameter in the middle. The equipment also provides for different types of adjustments and controls (crossing of rolls and roll bending) to correct distortion. Example is crossing the rolls slightly rather than having them truly parallel; results in increasing the nip opening at both ends of the roll. Less deflection at high operating conditions can be achieved by the use of stiffer rolls, based on higher modulus of elasticity steels or dual-steel construction. Another approach is to bend the roll so that the bending moment is applied to the end of each roll by having a second bearing on each roll neck. In turn a hydraulic cylinder loads it.

Calenders require high temperatures with little variations or fluctuations across the rolls during the application of the high pressures on the stock. Flow of stock relates to the friction between the stock and the roll faces, stock viscoelasticity, and pressure applied on the plastic. The first matching rolls provide initial control feeding plastic into the calender system. The final matching rolls provide the final roll thickness control of the sheet or film. Those matching rolls in between provide a gradual thickness metering action. Adjusting roll temperatures and speeds controls the final product dimensions. Roll loads run 1000 to 2000 lb/linear in. of roll face for soft sheeting, and occasionally approach 5000 lb/linear in. for thin, rigid material processed cool at 330F (166C) on larger rolls. Total connected horsepower can run from 2 yd./min. on 24 in. calenders, to as much as 8 to 10 for a large 36 by 96 in. machine on tough plastics.

Any unevenness in the temperature and pressure along the roll's length, that could include uneven temperature across the melt, is reflected as variations in the product thickness. Other causes of thickness changes across the web include nonhomogeneous rheology of the stock (Chapter 1), problems with material's lubricity, malfunctioning pressure and temperature sensors, equipment line control malfunctioning, use of damaged calender rolls, and so on. Also critical is the cooling of film or sheet that use multiple water-cooled rolls in the calender line with roll temperatures gradually reduced as the plastic travels downstream.

The sheet or film immediately passes through precision surfaced cooling rolls that are kept at precisely controlled temperatures and/or a cooling tower where the web can be festooned. At least two to ten to possibly 20 cooling rolls are used depending on the thickness of web and the speed of production line. With more cooling rolls the line permits slower cooling to room temperature eliminating a shock cooling situation for certain plastics that reduces physical and mechanical properties such as rigid PVC. If embossing is to be applied, the embossing roll precedes these cooling rolls. After leaving the last large diameter calendering heated rolls, the film can be literally dropped vertically into an embosser, usually with three rolls – that is the embossing roll itself, a cooling rubber roll, and a contact cooling to the rubber roll. Temperature accuracy is usually controlled within ±1C (±2F).

Since the heated plastic clings to the calender rolls the web does not drop off the last roll. It has to be pulled off evenly across the width of the roll. This is accomplished by the stripper roll which is normally positioned 3 to 6 in. (75 to 150 mm) from the last roll, and at a height that gives the sheet approximately 270° lap round the roll.

Overall after the heated plastic passes through the rolls it can go through operations of stripping, embossing, cooling, trimming, and wind-up. Because here the hot plastic is in contact with a comparatively cold roller, for PVC there may be a problem of plasticizer and moisture condensing on the metal surface of the stripper roll. This condensate will mark or, in the case of condensed plasticizer, attack the sheet surface. To overcome this damaging action the stripper roll is covered with a highly absorbent material such as cloth.

The thinner the sheet the greater the degree of roll cling, Thus the speed of the stripper roll must be varied with respect to the calender speed. Once the desired speed differential is set it is maintained. As the calender speed is altered, the stripper roll speed maintains a constant ratio with the calender speed.

Different types of controls are available to meet specific operating conditions (Chapter 3). Proper use of all controls is required to meet product performances and minimize costs. The controls can call for adjustments on different line equipment, such as the nip openings, roll bending, neckdown, and so on. As an example proper use of neckdown roll permits windups to be run faster than the final calender roll on many thin, unsupported film products. Calenders and take-offs are run almost synchronously on heavy gauge products. Films and sheets with a high gloss taken off a highly polished final calender roll tend to stick to the roll more than their matte counterparts. Very soft webs also tend to stick to the final calender roll. The fastest calender speeds are generally obtained in a median thickness range.

Trimming can be performed either on the calender or later when the sheet is cold just prior to winding. It is economically sound to trim at the calender stage where the material, owing to its existing temperature, can be readily conveyed back to the calender feed nip, to a set of rolls, an extruder feeder for recycling, or a granulator and blended with virgin plastic. Following cooling the plastic can be trimmed at the edges and wound. Trim material can account for up to 5% of the width depending on the line's operating efficiency. The target is to have as little trim as possible. This operation is to cool the sheet to ambient temperatures. If warm or hot sheet is wound up, high internal strains may be caused and blocking and de-embossing problems may be introduced. Ideally, sheet should be wound up at approximately 10C (50F).

Wind-up occurs at the end of the line. The two usual methods of winding into rolls are center-core winding and surface batching. Not all calendered sheets are wound up into rolls. They are also cut into panels by rotary cutters or automatic guillotines that may be installed instead of wind-up equipment. With center-core winding one end of the mandrel is fitted into a socket which is power driven. It requires that uniform sheet or film tension is used or the product will not be uniform in thickness, etc. As the roll increases in size the moment of inertia builds up and the take-up force per revolution increases. Unless the drive can compensate for this force increase, the winding tension varies throughout the roll. By appropriately adjusting the tensions, winding can be applied to rigid or flexible plastics. Methods used to overcome this tension situation include a slipping clutch between the mandrel and the drive, or more usually, having the drive to the mandrel transmitted by a motor drive. This action controls the sheet tension at a predetermined value regardless of the increasing diameter as the roll winds up.

To facilitate roll changing the winding station is usually duplicated, thus allowing one roll to wind while the other is being removed. Other auxiliary equipment can be included in the line such as orienting by stretching in the machine direction and/or transverse direction using the cooling rolls or setup bioriented stretching (Chapters 5 and 18), annealing, decorating, slitting, heat sealing, festooning, and so on.

Compounding/Blending

Different plastics, each with variations in type and quantity of additives, fillers and/or reinforcements, result in providing different processing conditions and end product performances. Important is the proper preparation of the plastic compounded stock to be processed based on weight as well as order of mixing. Stock prepared effects factors such as how the calender is to be operated, take-off thickness measurements, windup system requirements, and line speed controls. Other factors that influence the preparation of a stock is related to the finish (glossy, semi-matte, matte, etc.), product requiring coating or laminated to a substraight (fabric, plastic film or sheet, aluminum foil, etc.), embossed, etc.), or include if web is slit in line. With the finished product special properties may be required such as optical clarity and mono or biaxial orientation (Chapter 5).

Blending or compounding of the plastic with different additives and fillers is a critical part of the process, particularly of PVCs. The PVC compounds require heat stabilizers in order to be properly processed. Heat stabilizer system imparts during processing primarily heat stability, as well as adequate lubricating characteristics to reduce or control frictional heat. Stabilizers are also very efficient for plate-out resistance. Plate-out is a condition where the calender rolls and/or embossing rolls become coated with a deposit from the compound being processed that in turn interferes with obtaining an acceptable surface finish of the film or sheet. This deposit may start out as a soft, waxy material barely visible on the metallic contact surfaces of the processing equipment. When plate-out occurs the line has to be shut down and the contamination removed.

Processing

Because the plastic is processed between the required heat and its critical heat of degradation, the time of heat becomes extremely critical and an important part of the complete process. For example the processor will minimize the amount of melt in the nip of the rolls. The residence time of the plastic flux at high heat must be controlled and limited. PVC is especially sensitivity to heat and time at heat. What is required is proper setting of the machine controls and operation within set limits. The processing variables of a PVC plastic (such as flow, heat stability and softening point) are strongly influenced by polymerization technique, MWD, and the extent of any polymerization (Chapter 1).

Due to the plastic's viscosity, a melt shear effect is developed throughout the process. This shear is of prime importance between the calender rolls. The calender forms the web as a continuous extrusion between the rolls (Chapter 1). Unlike when processing just through a conventional extrusion line, the plastic mass cannot be confined when being calendered. Because of the lack of confinement, the shear effect and a broad melt band are essential aspects of calendering.

To improve PVC melt flow the stock is subjected to fluxing or fusion. It is the heating of the vinyl compound to produce a homogeneous mixture. Fluxing units used in calendering lines include batch-type Banbury mixers, Farrel continuous mixers (FCMs), Buss Ko-Kneaders (BKKs), and planetary gear extruders (PGEs). The dry blend is fed into the mixer/extruder. Proper mixing within a short dwell time and heat transfer control contributes to an improved product. During fluxing, each particle receives the same gentle treatment, generating less heat history and producing more uniform feed rate, color, gauge thickness, web surface, and so on. The feed can discharge onto a two-roll mill. Operating this way, it provides for a second fluxing action, mainly for working in scrap or for convenience as a buffer.

Rigid PVC manufacturers usual prefer the L-type with four to seven rolls being fed from the floor level. Since there is no disturbing vapors from lower calender rolls within the pickoff area, it is preferable to have the pickoff rolls on an elevated level. Flexible PVC is commonly processed using a 4-roll inverted L- or an F-type. A universal five roll L calender is used for rigid or flexible PVC film. It provides heat stability and superior film control with good surface appearance. The major difference between this universal machine and the others is in mounting and placement of the first roll. These systems enable the plasticizer-saturated vapors to escape via the usual suction hood located above the calender where they are filtered before being released to the atmosphere.

The stock delivered to the first calender nip needs to be well fused, homogeneous in composition, and relatively uniform in temperature. The optimum average temperature for good fusion depends on the formulation. A rigid PVC formulation based on medium molecular weight plastic (intrinsic viscosity of 0.90 to 1.15)[211] has a typical optimum temperature of 180 to 190C (355 to 375F) at the first calender nip. For best calendering, there should be no cold volume elements below 180C (356F) and no hot spots above 200C (392F). Required is close control of temperature to ensure proper fusion and mixing conditions.

This interaction depends on stock temperature and in turn on the performance of PVC melts. Flexible PVC is normally calendered at temperatures of 10 to 20C (50 to 68F) lower than rigid PVC. In flexible PVC production, a short single screw extruder acting as a strainer filters out contaminants from stock before reaching the calender. This important method is not applicable to rigid PVC because it drastically increases the head pressure and the consequent overheating would cause the stock to decompose.

Market

Products from calenders go into many different markets such as credit cards, upholstery, luggage, water reservoir, rainwear, loose-leaf book, and footwear. Different plastics are used such as ABS and ABS/PVC alloys go into margarine pack, luggage, panels, and chlorinated PE go into roofing, and pond liners. There are unsupported and supported as well as rigid products and coated substrates. Unsupported flexible PVC is in label tapes, flooring tiles, pool liners, crop covers, raingears, tank linings, packaging liquids, shower curtains, auto interiors and trims, ditch linings, book binders, electrical and pipe wrap tapes, auto crash pads, inflatables (such as air beds, swim rings, and children's paddling pools), headliners, mattress covers, crib linings, baby pants, convertible rear windows, hand bags, moisture barriers, chemical resistant panels, and pressure-sensitive adhesives.

Supported rigid PVC is in window shades, wall and floor coverings, tablecloths, woodgrain laminations, book liners, and labels. Rigid PVC is in hardwares and food packs, trays, pharmaceutical packs, credit cards, lighting fixtures, ceiling tile facings, woodgrains, laminate covers, signs, tank linings, corrosive duct works, thin tapes, strapping tapes, trays, helmet liners, and printers' products.

Coated substrates involve different materials such as coated credit cards, paper, woven and nonwoven textiles, plastic or aluminum films and sheets, and roll coverings. Calender lines can process one coated side, both sides, or laminated (multiple substrates coated between each substrate). Calender with three rolls is usually sufficient for one-sided coating. However four rolls are used for extremely thin coatings. The 4-roll calender can be used for double-sided coating that is applied simultaneously on both sides. Specialized calendering equipment is used for certain products such as credit cards, floor tiles, and window curtains.

The application of flexible sheet material to the surface of mandrels, called roll covering, is used in a variety of industries that include printing, paper, textiles, steel, office machinery, plastic fabricating lines, and many others (Figure 9.4). Their use includes to compress, drive, emboss, convey, protect, dye, suction, treat, pickle, paint, and print.

Calendering vs. Extrusion

Calendering and extrusion lines (Chapter 5) produce film, sheet, and for applying plastic coatings to textiles, paper, or other supporting material. Table 9.1 provides comparison in fabricating PVC film. The extrusion process provides flexibility, when compared to calendering, that includes ease of changing product thicknesses, widths, materials, and provides for short production runs.

Calendered sheet is usually less glossy than extruded material. Calendering may be preferable for certain applications requiring its higher tensile properties, product uniformity, and unusually close gauge

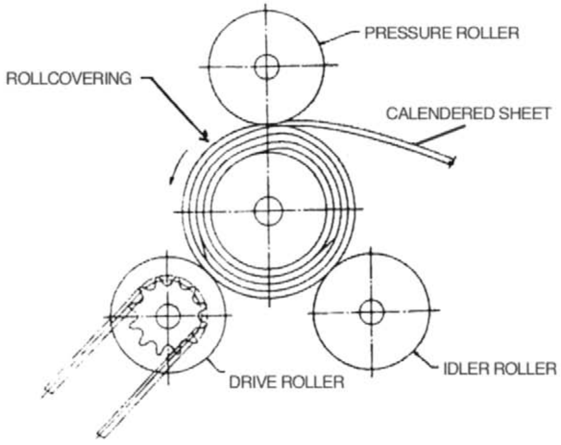


Figure 9.4 Example of roll covering

Table 9.1 Example of comparing calendering and extrusion processes

	Calender	Extruder flatdie	Extruder Blown film	Extruder flex-lip
Relative resin cost	lowest	low	higher	higher
Machine cost ($ million)	1-10	1–4	0.3–1	0.3–1
Rate and range (lb h^{-1})	800–8000	500–1500	600 ($4\frac{1}{2}$ in)	750 ($4\frac{1}{2}$ in)
Product gauge range (in)	0.002–0.050	0.002–0.005	0.001–0.003	0.001–0.125
Sheet accuracy (%)	3 (1–5)	3 (1–5)	10	10
Time to heat (h)	6	5	3	3
Time for startup	2–5 min	10 min	2 h	5 h
Gauge adjust time	seconds	seconds	5–30 min	5–30 min
Autogauging, capability	yes	yes	no	no
Color or product change time	5–30 min	10–40 min	30–60 min	30–60 min
Windup speed (ft min^{-1}) average (max.)	80 (150)	60 (80)	15 (20)	15 (30)
Limitations	High capital cost, heat time	Lower rate, versatility problem	Poor accuracy, long on startup time, low rate, degradation, reduced versatility	
Applications and advantages	Versatility, high rate, accuracy, ease and, adjustment ease at reprocess	Accuracy, gauge adjust, reduced cost	Low investment, multiplant capability, thin gauge (0.003 in and under) and heavy gauge (0.050–0.125 in)	

control. Extrusion of colored films or sheets requires the extruder to be cleaned and purged when changing colors. A calender requires a minimum of cleaning between color changes. Calendering definitely has to be used for long production runs in order to be economically profitable, producing smooth and other finishes at higher speeds. In general, plastic materials, such as PE, PP, and PS film and sheet, are usually produced through the rather conventional extrusion lines. To produce PVC film and sheet in large quantities, calendering is almost always used since the process is less likely to cause degradation than is extrusion as well as having dimensional and cost advantages.

The capital equipment and replacement parts in calendering lines are more expensive. A web thickness between 0.05 to 0.50 mm (0.002 to 0.020 in.) is generally the kind of plasticized film and sheeting produced by calender lines. For extremely light gauges, those under 0.02 mm (0.001 in.), calendering could become impractical or damaging to the equipment. The reasons include factors such as, for certain materials, there exists poor strength of the thin webs and also very high forces develop on the matting heavy-duty rolls. Heavy/thick gauges, such as sheeting over 0.50 mm (0.020 in.), calendering may not be the optimum method of production. The reason is that there may not be enough shearing action that can be put into the rolling banks to keep the compound at uniform temperature. In addition, the separating forces on the rolls become so low that gauges variations could become prohibitive.

In summarizing the productivity of calendering the type of calendered product is significant. Heavy sheeting, the easiest product to make can run at high speeds, depending on fluxing and feeding capacity. If the product is post-treated with laminating to a substrate, embossed, printed, or top-coated, production can be even greater since defects in the sheet can be masked.

Thin flexible film, sold straight off the calender, is difficult to make because of layflat problems, although speeds of 100 yd/min. at the calender and 125 yd./min. at the winder are common. Some post-treated rigid films can run at 80 yd./min., but other rigid sheets of the glossy or polished variety are limited to about 20 to 35 yd./min. for top quality. Thus, the rates through a line may range from a low of 800 to a high approaching at least 9000 lb./hr.

The main disadvantages of calendering are large initial investment costs and lengthy heat up times. The advantages that make the calender ultimately the most desirable method of all are maximum rates and speeds, accuracy of gauge, speed of gauge adjustment, processing and product range versatility, lower raw plastic costs, high on-stream time factors, fast on-line time, and case of accommodation of automatic gauging and control.

10 COATING

Overview

Coated products using thermoplastics (TP) and thermoset plastics (TS) are literally all around us worldwide. This large industry produces two broad categories of coatings, namely, the trade sales and the industrial finishes. Trade sales, or shelf goods, include products sold directly to consumers, contractors, and professional painters for use on construction or painting, refinishing, and general maintenance.[261] These coatings are used chiefly on houses and buildings, although a sizeable portion is used for refinishing automobiles and machinery. Also included are electric/electronic, packaging, building, household and industrial appliances, transportation, marine, medical,[474] clothing, and many more.

Industrial finishes, or chemical coatings, encompass a myriad of products for application by manufacturers in the factory or for industrial maintenance and protection. They are custom made products sold to other manufacturers for such items as automobiles, appliances, furniture, ships and boats, metal containers, streets and highways, and government facilities.

Coating compounds are used to cover the surfaces of many materials from plastic to paper to fabric to metal to concrete and so on. Many plastics produced are consumed as coating materials, including paints, primers, varnishes, and enamels. Metals may be surface coated to improve their workability in mechanical processing. Substrates protected from different environmental conditions basically include the metals (steel, zinc, aluminum, and copper), inorganic materials (plaster, concrete, and asbestos) and organic materials (wood, wallboard, wallpaper, and plastics). Different technical developments continue to occur in the coating industry, which permit the use of a variety of plastics. It is possible to formulate surface coatings that are suitable for each and every kind of material.

Type

Coatings are generally identified as paints, lacquers, varnishes, enamels, hot melts, plastisols, organosols, water-emulsion, solution finishes, nonaqueous dispersions, powder coatings, masonry water repellents, polishes, magnetic tape coatings, overlays, gels, compound, etc. Paint and some of the other coatings may be identified as interior or exterior type.[262] Each type usually has its own identification such as the lacquer coating is a cellulosic composition that dries by the evaporation of the solvent. Varnish identifies a mixture of plastic and oil. The term paint is often used to cover all the coating categories as though it was synonymous with coating; the terms are often used interchangeably. Paint coatings consume by far the largest quantity of coating material. However the other coating processes are important and useful. All these surface coatings represent a large segment of the overall plastic and chemical industries.

There are 100% resin coatings such as vinyl-coated fabrics or polyurethane floor coverings. The usual components of paint and other coatings are the binder (resin), pigment, solvent, and additive. The binder provides the cohesive forces that hold the film together and holds the coating film to the substrate. The pigment that is in a fine powder provides color and properties such as hardeners and resistance to abrasion and weathering. The pigment has a considerable influence on the consistency (viscosity) of the paint and in turn on its application properties. The volatile liquid solvent provides the means to dissolve the binder. Coating systems may contain additives to meet certain processing and/or performance requirements. Examples are stabilizers, plasticizers, dryers, wetting agents, flattening agents, and emulsifiers.

The binder is the most important of the components and is always present in a manufactured paint. It usually represents 40 to 50wt% of the paint. Many of the properties of paints and related products are determined directly by the nature of the binder. For this reason paints are often classified and may even be named according to the type of binder. Binders are identified according to type of drying. The physical and chemical drying types relate to how they are formulated. The physical film type results in the evaporation of the solvent or of dispersion medium in the case of paint lattices. Chemical film type has an oxidative drying constituent such as drying oils, varnishes, linseed oil, tung oil, and alkyd plastic modified with drying oils.

Coating vehicle usually identifies a combination of binder and volatile liquid. It may be a solution or a dispersion of fine binder particles in a nonsolvent formulation. No pigments are included if a clear, transparent coating is required. The composition of the volatile liquid provides enough viscosity for packaging and other application, but the liquid itself rarely becomes part of the finished coating.

Film coating can involve chemical reaction, polymerization, or crosslinking. Some films only involve coalescence of plastic particles. There are various mechanisms involved in the formation of plastic coatings. They can be identified as follows:

(a) dispersions of a plastic in a vehicle followed by removal of the vehicle via evaporation or heat baking; result is the plastic coalesces to form a film of plastisol, organosol, water-based, or latex paint;

(b) pigments in oil that polymerizes in the presence of oxygen and drying agents that include alkyd, enamels, and varnishes;

(c) coating formed by chemical reaction, polymerization or crosslinking of TS plastics;

(d) plastic dissolved in a solvent followed by solvent evaporation to leave a plastic film of vinyl lacquer, acrylic lacquer, alkyd, chlorinated rubber, cellulose lacquer, etc.;

(e) coatings formed by dipping in a hot melt of plastic such as polyethylene, acrylic, and vinyl;

(f) coatings formed by using a powdered plastic and melting the powder to form a coating using many different TPs.

There are cold curing coatings and baking coatings that principally use TS plastics. They include polyurethane, epoxy, polyester, alkyd, acrylic, phenolic, and urea-formaldehyde. Curing occurs in which drying is by a chemical reaction between the molecules of the binder (Chapter 1). If the reaction occurs at room temperature the products are described as cold curing coatings. If temperatures of 70C (158F) or higher are necessary to cause rapid reaction, the materials are known as baking coatings. In view of the many different kinds of chemical reactions that are now used to produce insoluble coatings, the term convertible coating is used.

There are the popular paints containing water. They are called water-base, water-thinned, aqueous, etc. These water-based paints include latex or emulsion paints made with plastics (acrylic, polyvinyl acetate, etc.). Over a century ago the original water-base paints used casein and the emulsion oil paints containing alkyd resin and water. Latex paints using butadiene-styrene developed during the 1940s. They were referred to as rubber base paints that lacked ruggedness. During the 1950s the acrylic emulsion type paint was introduced for interior and exterior use. These more expensive latex-plastic coatings continue to be very popular since they eliminate solvent fumes, reduce fire and explosion hazards, improve working conditions, and reduce fire insurance rates.

Plastic behavior

Coatings are composed of TP or TS plastic. Plastics are applied in one operation or built up during drying processes. During mixing they can be varied in relation to the end use for which they are required. These plastics permit preparing coatings that can repeatedly meet close performance tolerance requirements. TPs coating films require that they have a minimum level of strength. This strength depends on the end use requirement of the product. Film strength depends on many variables with molecular weight (MW) being very important (Chapter 1). MW varies with the chemical composition of the binder. With this type of system a large fraction of the solvent evaporates in the time interval between the coating leaving the orifice of the spray gun and its deposition on the surface being coated. As the solvent evaporates, the viscosity increases and soon after application, the coating reaches the dry-to-touch state and does not block. However if the film is formed at low temperature such as 25C (77F), the dry film contains several percent of retained solvent.

These TP based coatings have a low solids content because their relatively high MWs require large amounts of solvent to reduce the viscosity to levels low enough for application. The increasing costs of solvents and air pollution regulations limiting the emission of volatile organic compounds (VOCs) have led to the increasing replacement of these coatings with lower-solvent or solventless coatings. However large-scale solvent-coating production systems continue to be economically beneficial when used with available solvent recovery systems.

Paints containing water (latexes) have a dispersion of high-MW plastic in water. This condition results in the desirable low solvent emission. Because the TP is not in solution, the rate of water loss is almost independent of composition until it is close to complete evaporation.

When a dry film is prepared, the forces that stabilize the dispersion of TP particles must be overcome and the particles must coalesce into a continuous film. The rate of coalescence is controlled by the free volume available, that in turn depends mainly on T_g (Chapter 1).

TSs not properly stored can lose their stability before use. With TS plastics target is to meet the required storage stability of the coating before application and time/temperature required crosslinking curing of the film after application. The processing of TSs is different than TPs (Chapter 1).. Stability and curing behavior is related to the amount of solvent used. Adding more solvent increases storage life. When the solvent evaporates after application, the reaction rate increases initially. Although it is advantageous to reduce solvent concentration as much as possible, the problem of storage stability has to be considered for systems with a higher solids content. The mechanical properties of the final film depend on the glass transition temperature (T_g) for the crosslinked plastic and the degree of crosslinking (Chapter 1). The average functionality, equivalent weight of system, and the completeness of the reaction (complete cure of the TS) affect the crosslink density.

Process

Overview

Different methods of coating are used to meet different coated product requirements (Table 10.1). The coating materials are in different forms ranging from liquids to solids. They include emulsion, latex, dispersion, lacquer, powdered plastic composition, plastisol, organosol, rubber composition, hot-melt, reacting TS compound, etc. The product could be plastic film, paper, paperboard, woven fabric, plywood, nonwoven fabric, steel sheet, aluminum foil, irregular flat or shaped products, etc.[260]

The processes include roller coating (Figure 10.1), knife or spread (Figure 10.2), transfer (Figure 10.3), dip, vacuum, in-mold via reaction injection molding (Chapter 12), electrodeposition, spraying, fluidized bed, brushing, floc, microcapsulation, radiation, and many others. Calendering of a film to a supporting material is also a form of coating that tends to be similar to roll coating (Chapter 9). Processes are also used to coat specific products such as floor covering and foamed carpet backing. Popular method is by extrusion (Figure 10.4) (Chapter 5).

Table 10.1 Examples of coating processes

Coating method	coating speed (m min^{-1})	Viscosity range, (m Pa s)	Wet-coating thickness range (μm)
Air knife	15–600	1–500	25–60
Brush	30–120	100–2,000	50–200
Calender	5–90		100–500
Cast-coating	3–60	1,000–5,000	50–500
Curtain	20–400	100–20,000	25–250
Dip	15–200	100–1,000	25–250
Extrusion	20–900	30,000–50,000	12–50
Blade	300–600	5,000–10,000	12–25
Floating knife	3–30	500–5,000	50–250
Gravure	2–450	100–1,000	12–50
Kiss roll	30–300	100–2,000	25–125
Knife-over-blanket	3–30	500–5,000	50–250
Knife-over-roll	3–60	1,000–10,000	50–500
Offset gravure	30–600	50–500	12–25
Reverse roll	30–300	50–20,000	50–500
Reverse-smoothing roll	15–300	1,000–5,000	25–75
Rod	3–150	50–500	25–125
Sprays			
Airless spray	3–90	–	2–250
Air spray	3–90	–	2–250
Electrostatic	3–90	–	2–250
Squeeze roll	30–700	100–5,000	25–125
In situ polymerization	undetermined	liquid or vapor	6–2.5
Powdered resin	3–60		25–250^c
Electrostatic spray			20–75^c
Fluidized bed			200–2,000^c

Spray Coating

Spray coating is used before and after a product is assembled particularly if already assembled and has complex shaped and curved surfaces. Many different types of spray equipment are in use to handle the different forms of paints used. They are classified by their method of atomization (airless, air, rotary, electrostatic, etc.) and by their deposition assist (electrostatic or nonelectrostatic, flame spray, etc.). Spraying techniques may fall into several of these categories. They range from simple systems with one manual applicator to highly complex, computer-controlled, automatic systems. They can incorporate hundreds of spray units. Automatic systems may have their applicators mounted on fixed stands, on reciprocating or rotating machines, on robots, and so on.

Flame Spray Coating

Flame spray coating involves blowing a plastic powder through a flame that partially melts the powder and fuses it as it contacts the substrate. The

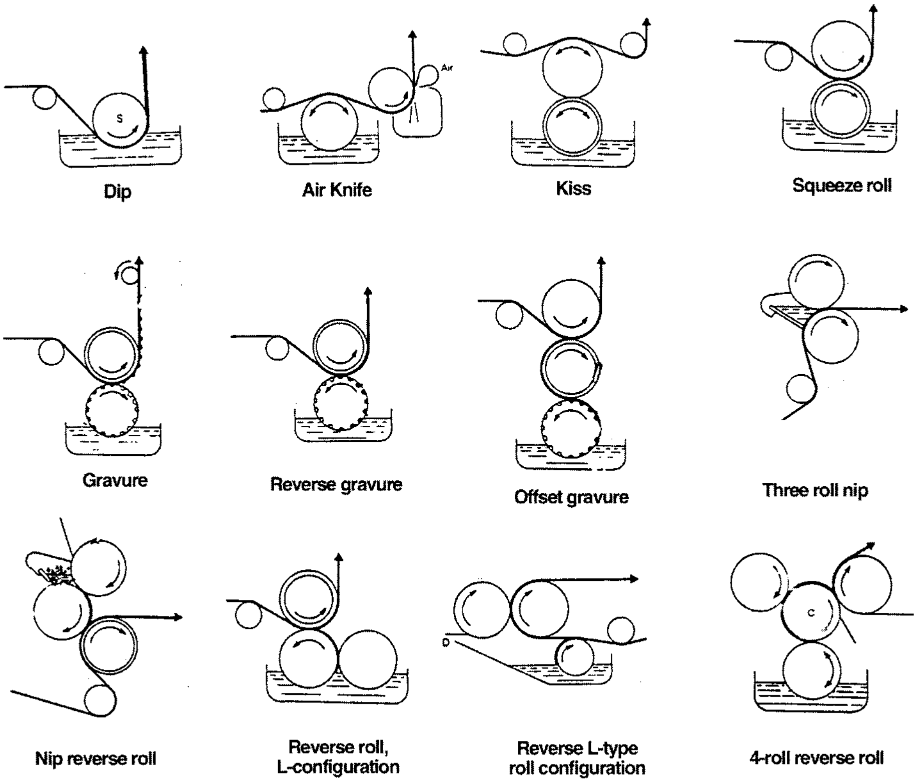

S
Dip
Air
Air Knife
Kiss
Squeeze roll
Gravure
Reverse gravure
Offset gravure
Three roll nip
Nip reverse roll
Reverse roll, L-configuration
D
Reverse L-type roll configuration
C
4-roll reverse roll

Figure 10.1 Simplified examples of basic roll coating processes

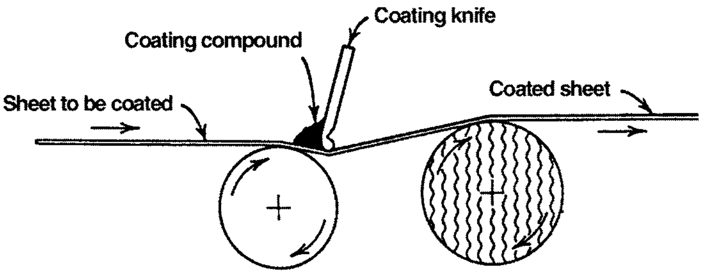

Coating knife
Coating compound
Sheet to be coated
Coated sheet

Figure 10.2 Example of knife spread coating

part's surface is preheated with the flame. The usual approach is to coat only a few square meters at a time, so the temperature can be controlled. The flame is then adjusted. When coating is completed, the powder is shut off and the coating is post-heated with the flame. Flame spraying is particularly useful for coating products with surface areas too large for heating in an oven. Disadvantages are the problems associated with an open flame and the need for skilled operators to apply the coating.

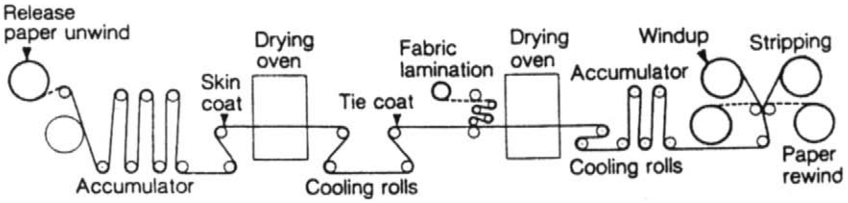

Release paper unwind
Accumulator
Skin coat
Drying oven
Tie coat
Cooling rolls
Fabric lamination
Drying oven
Accumulator
Cooling rolls
Windup
Stripping
Paper rewind

Figure 10.3 Examples of transfer paper coating line

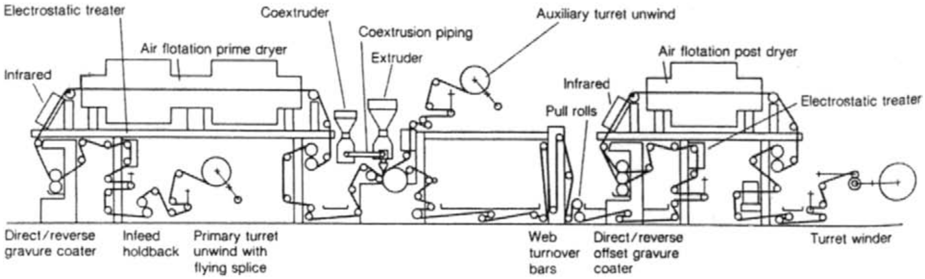

Electrostatic treater
Coextruder
Coextrusion piping
Air flotation prime dryer
Extruder
Infrared
Auxiliary turret unwind
Air flotation post dryer
Infrared
Pull rolls
Electrostatic treater
Direct/reverse gravure coater
Infeed holdback
Primary turret unwind with flying splice
Web turnover bars
Direct/reverse offset gravure coater
Turret winder

Figure 10.4 Example of an extrusion coating line

Roll-Coat Finish

Referred to as “roll-coat” because they are applied to coiled metal by the reserve roller-coating technique (similar to offset printing). A wide variety of techniques are used providing a broad range of decorative effects. Their primary advantage is that they can withstand metalworking or plastic-working operations without any surface damage resulting. This behavior permits coatings to be applied before product fabrication (bending, etc.), eliminating finishing steps afterwards, and can thereby cut costs.

With the wide range of plastics, there are roll coat finishing types that are extremely flexible; capable of taking very severe forming operations with no cracking or loss of adhesion. They are used for applications involving rigorous bends, which before prohibited the use of precoated metal for lack of finishes with enough formability. An example is a vinyl low cost coating system (as well as other plastics such as acrylics and polyesters), it can satisfactorily withstand one of the most complex bends or back-to-back bend cycles.

Spread Coating

This technique involves that the material to be coated passes over a roller and under a long blade or knife. The plastic coating compound is placed on the material just in front of the knife and is spread out over the material to be coated. Coating thickness is basically regulated by the speed at which the material is drawn under the knife and the position/spacing of the knife. The usual coating material is a plastic melt but also used are plastics in the form of fine powders.

Floating Knife Coater

This system applies a uniformly controlled amount of coating to a web or a sheet substrate. The choice of coater (spread, spray, roll, dip, and air knife) depends on the type coating and the substrate and factors such as solvent removal, drying, and production rate required. The equipment includes a knife or bar coater that scrape off a heavy layer of coating liquid to the desired thickness. The floating blade coater depends on web tension and blade contour to control thickness, whereas the knife-over-roll allows setting the knife at a fixed distance from the roll. Modifications of knife contour control coatings of various viscosities and rheologies exist.

There are many types of roll coaters available such as the reverse roll arrangement (Figure 10.1). It has the roll rotating counterwise to the substrate travel. This allows control of coating thickness by adjusting the gap between the metering roll or applicator roll as well as using both. The reverse roll coater works best at applying coatings that are thixotropic or at least Newtonian (Chapter 1).[211] Coatings of a dilatant nature generally run at lower speeds, because of the high shear between the applicator roll and substrate.

Fluidized Bed Coating

In fluidized bed coating, a product to be coated is heated and then immersed in a dense-phase air fluidized bed of powdered plastic; the plastic adheres to the heated object and subsequent heating provides a smooth, pinhole-free coating.

Powder Coating

Powder coating is a solventless system; it does not depend on the use of a solvent. It uses the performance constituents of solid TP or TS materials. It can be a homogeneous blend of the plastic with fillers and additives in the form of dry, fine particles of a compound similar to flour. Advantages of powder coating include minimum air pollution and water contamination, increased performance with coating, and consequent cost savings. It has many of the same problems as solution painting. If not properly formulated, the coating may sag, particularly for thick coatings, show poor performance when not completely cured, show imperfections such as craters and pinholes, and have poor hiding with low film thickness. Various methods are used to apply powder coatings.

Electrostatic Spraying

Electrostatic spraying is based on the fact that most plastic powders are insulators with relatively high volume resistivity values. They accept a charge (positive or negative polarity) and are attracted to a grounded or oppositely charged object (that is the one being coated).

Metal Coil Coating

Coil coating with plastics is a very big business worldwide. Many different products are coil coated such as venetian blinds, metal awnings, metal sidings, automobile trims, light reflectors, luggage, and metal doors. Processes involve high speed and continuous mechanized procedures for paint coating one or both sides of a coil of sheet metal at speeds of at least 500 ft/min. Coating equipment, metal cleaning, and new paint formulations provide ease of formability with environmental durability. The basic operations in the process involve unwinding steel coil, chemically pretreating steel, reverse roll-coating paint, baking paint, applying additional coatings in certain processes, cooling coated metal, inspection, and rewind coil. Coil coatings can contain up to 40wt% of solvents. Thus this industry has heavily invested in equipment to deal with the safe recovery of solvents.

Likely challenge to the current solvent technology includes radiation curing and powder coating. Coil coats are thin (about 30 μm wet thickness) but contain a high pigment loading. Thus UV curing is less suitable than electron beam curing. The application of this technology requires a change to the plastic system and acrylic oligomers are the most suitable for this application. This system can be processed without solvents. If a reduction of viscosity is required, it can be accomplished by the use of plasticizers (the best candidates to date are branched phthalate and linear adipate) and/or reactive diluents such as multifunctional monomers.

Radiation curing has a disadvantage because of its high capital investment but it does have an economical advantage because the process is very energy efficient. Previous experiences with radiation curing technology show that the process has been successfully implemented in several industries such as paper, plastic processing, and wood coating where long term economic gains made the changes viable. The National Coil Coaters Association, Chicago, Ill., organized in 1962, has developing industry standards, exchange of technical information, preparing technical manuals and keeping records of sales growth.

Property

Plastic coating materials have been exposed to all kinds of performances and environments to meet the many different requirements that exist in the many different applications. Included are corrosion and chemical resistant, fire retardant or non-flammable, strippable, heat resistant, electrical insulation, and others reviewed above (Chapter 2). What follows is information that highlight some of the properties and tests that influence the performance of coatings.

Thermal Control

Since 1960, the area of passive thermal control of space vehicles and their components has emerged into a role of increasing importance among the space sciences. In contrast to the active thermal control, passive thermal control offered the advantages of no moving parts resulting in the absence of mechanical failure with weight savings. Factors in controlling the space vehicle temperature by passive means are the optical characteristics of the surface of the spacecraft vehicle, that is solar absorption and emittance. In order to function as a thermal control surface, a coating must be stable and flexible, with respect to its optical properties, to the effects of the space environment, primarily UV radiation, particulate radiation, high vacuum, and temperature.

Germ-Free Coating

Past attempts to create surfaces with inherent bactericidal properties capable of rendering them germ free have been unsuccessful. Researchers at Northeastern University (NEU), working with colleagues at the Massachusetts Institute of Technology (MIT) and Tufts University (TU) (all in the Boston, MA area), believe they may have developed a method for creating permanently germ-free dry surfaces.[262] They speculated that previous efforts to design dry bactericidal surfaces failed because the polymer chains that made up the material were not sufficiently long and flexible enough to penetrate bacterial cell walls.

Their research has demonstrated that covalent attachment of N-alkylated poly(4-vinylpyridine) (PVP) to glass can make surfaces permanently lethal to several types of bacteria on contact. The group found a narrow range of N-alkylated PVP compositions that enable the polymer to retain its bacteria-killing ability when coated on dry surfaces. It is believed that these are the first engineered surfaces proven to kill airborne microbes in the absence of a liquid medium.

11 CASTING

Introduction

Casting applies to the formation of an object by basically pouring a liquid plastic into an open mold or surface where it completes its solidification.[481] Either liquid thermoplastic (TP) or thermoset (TS) plastic is used. With TPs after pouring it hardens. The TSs chemically react and cure to form a rigid product (Chapter 1). The choice of casting material, the type of mold, and the method of fabrication often depend on the application. Production is rarely automated, but automation may be used when the economic benefits exist such as long or specialty fabrication runs. Casting may be used to fabricate different shaped products, rods, tubes, etc. in an open or closed mold. Film and sheeting is also made by casting directly into a flat open mold, casting onto a wheel, continuously moving turntable, conveyor belt, or by precipitation in a chemical bath.

Extensive use is made in embedding in the plastic various ornamental or utilitarian objects. The process provides means to easily incorporate different product requirements such as coloring and texturing. The plastic mixture may contain pigments, fillers, plasticizer, and other chemical additives. They can include reinforcements providing aesthetic to increasing strength (Chapter 15).

One essential difference between casting and molding processes is that pressure need not be used in casting (although large-volume, complex parts can be made by low pressure and/or vacuum casting methods). Another difference is that the starting material is usually in liquid form rather than the usual solid plastic used in other processes. There is also the difference that the liquid could be a monomer rather than the plastic used in most other processes and in turn the monomer is converted to a polymer/plastic (Chapter 1).

This process has the advantages of low cost equipment, but is a relatively slow process and labor intense. Casting to fabricate certain products (complex shapes, etc.) could require skill, especially for large castings and the method tends to be very much of an art.

Plastic

Generally plastics that are free flowing and have low surface tensions with low viscosities are used for castings of intricate shapes and fine detail in design. Low-viscosity plastics are also more suitable for producing bubble-free castings. High-viscosity systems usually produce castings with better physical properties than do low-viscosity plastics. Handling of high-viscosity plastics requires closer attention to handling procedures since they are usually more difficult to process. Most plastics suitable for castings are two-component systems. A specified amount of hardener or accelerator is added to the plastic. It is important to ensure that thorough mixing takes place to maximize performance. Prior to pouring the compound into a mold, it is usually coated with a mold release agent. For fabricating certain products air is removed usually by a vacuum system prior to the plastic solidifying.

Depending on the plastic to be cast, solidification takes place at either room temperature or elevated temperatures. With room temperature systems chemical reaction occurs with the liberation of heat. The rate of heat dissipation can influence the performance and aesthetic characteristics of the hardened product. In thin sections, where a large area in relation to the total volume of the plastic is exposed, the heat of the exothermic reaction is dissipated rapidly and the temperature of casting is not very high. Thin sections can be cast at room temperature with no danger of cracking. When the rate of heat is excessive, application of heat may be necessary to properly control cure rate.

During casting bubbles or voids can be present. Sometimes they are invisible and other times they are visible but not materially damaging. During casting damaging or unwanted bubbles could be present due to material preparation and/or during processing. Methods for their removal exist. Air is present in the plastic with its hardener or catalyst or other additives and reinforcements. The bubbles could be due to air alone or moisture due to improper plastic material drying, compounding agent volatiles, plastic degradation, or the use of contaminated regrind. So the first step to resolving this problem is to be sure what problem exists. A logical troubleshooting approach can be used.[3]

Process

Different casting processes are used. They tend to overlap and could be identified by other processing methods. An example is liquid injection molding that can be identified as injection molding (Chapter 4) or reaction injection molding (Chapter 12). Many decades ago the reaction injection molding process was initially called liquid injection molding.

In some cases, the chemical reaction takes place during a casting process that converts a low molecular weight monomer into a high molecular weight thermoplastic (Chapters 1 and 2). The most common examples are acrylics and nylons. In other cases, polymerization and crosslinking take place simultaneously in the casting process, leading to thermosets. Examples include polyurethane resins (PUR), unsaturated polyester plastics (UP), epoxy plastics (EP), and silicone plastics (Si).

Exothermic heat curing systems can be used when processing at room temperature by the addition to the plastic additives and/or promoters. They are used to provide the necessary heat through chemical reactions. This reaction has to be controlled so that overheating will not occur, particularly large parts where damage could occur such as voids and not meeting dimensional requirements.

In addition to the conventional liquid pouring casting process others are used that includes investment casting that dates back centuries ago. Early Egyptians developed investment casting to make jewelry where sculpture wax was dipped in a ceramic slurry, then dryed, and heated to remove the wax. In turn the ceramic cavity received molten metal to form the desired finished part. This technique continued to be used with modifications that initially led to the casting of different materials that included plastics. Other systems evolved such as the so-called lost-wax or soluble core wax. Later low melting eutectic alloys were used providing a means to high production complex castings (Chapter 15).

The centrifugal casting process, that is also called centrifugal molding, is a method of forming plastic in which a dry or liquid plastic is placed in a rotating mold such as a pipe (Chapter 13). As it rotates around a single axis, heat is applied to the mold. The centrifugal force induced will force the molten plastic to conform to the configuration of the inside mold cavity. This method is different than rotational molding since it rotates only around one axis. Products such as tubing, pipes, and tanks (excluding end-caps), which have a circular-cylindrical shape, can be made of unreinforced or reinforced fiber glass plastics (GRP) by the centrifugal casting process. In the case of discontinuous fiber reinforcement, a mix of chopped fibers and pre-catalyzed liquid plastic is dispensed along the axis of a rotating cylindrical tool. As the material falls on the inside of the tool surface, it is entrained and centrifugal forces help compact it into a uniform layer, also keeping it in place during cure. Successive passes along the length of the cylinder can build up thickness. The final inner surface although not as good as the outer surface is reasonably smooth. Features can be formed in the outer surface, (flanges, threads, ribs, etc.) if the mold is made of suitable sections to allow the extraction of the finished product. The process can be modified to allow continuous pipe production.

There is a modified centrifugal casting process that produces continuous filament reinforced TP pipes/tubes with precise fiber placement and smooth internal and external surfaces. TPs such as nylon and polypropylene have been reinforced with fibers such as glass and carbon. Products such as automotive drive shafts and bearings have been fabricated with fiber volumes up to 60wt%. These tubes have very low rotational unbalances and tight tolerance of wall thickness (Chapter 15).

The process called TER-centrifuging (Dr Ing H. Schurmann, Technische University Darmstadt, Germany) starts by winding dry reinforcing fibers around a thermoplastic tube that can be made by extrusion or injection molding. The fibers can be arranged to meet a specific load requirement. The tube and fibers are then loaded into a casting mold, rotated at a controlled rate, and heated. As the molten plastic tube rotates, plastic impregnates the fibers.

There is the dip casting process, also called dip coating or dip molding. It is a process of submerging a hot molded shape, usually metal, into a fluid plastic. After removal and cooling, the product around the mold is removed from the mold.

Slush casting, also called slush molding or cast molding, is extensively used. It is a method where TPs in a liquid form are poured into a hot mold that is stationary or moving where a viscous skin forms. The excess slush is drained off, the mold is cooled, and the molding stripped out. Used to produce rain or snow boats, auto instrument panels, over shoes, corrugated and non-corrugated complex tubes, caps, etc.

With the solvent casting a plastic compounded with its constituents (solvent, stabilizers, additives, plasticizers, etc.) is carefully prepared at a certain rate of mixing. These soluble plastics are poured into a mold or on a moving belt to form film where heat is applied using heat control zones to prevent formation of blisters. The rate of solvent evaporation is inversely proportional to the square of the thickness. To reduce cost and meet regulations, solvent recovery systems are used that have explosive-proof hazard safety capabilities. There are also systems that use water-based solvent solutions such as polyvinyl alcohol plastic.

Spin casting can use plastic molds, such as silicone, to produce close tolerance, highly cost effective, limited production in a variety of materials. The process uses easily adjustable centrifugal force to inject liquid thermoset plastics into a circular disc-shaped elastomeric mold under pressure, completely and rapidly filling the mold cavities.

A simple non-mechanical version of reaction injection molding (Chapter 12) or liquid injection molding is foam casting. Foaming components are poured into a mold cavity that is usually heated (Chapter 8).

Different foundry casting techniques are used. Included are plastic-based binders mixed with sand. Various types of molds and cores are produced that include no-bake or cold-box, hot-box, shell, and oven-cured. Usual binders are phenolic, furan, and thermoset polyester. There is the foundry shell casting, also called dry-mix casting. It is a type of process used in the foundry industry, in which a mixture of sand and plastic (phenolic, thermoset polyester, etc.) is placed on to a preheated metal pattern (producing half a mold) causing the plastic to flow and build a thin shell over the pattern. Liquid plastic pre-coated sand is also used. After a short cure time at high temperature, the mold is stripped from its pattern and combined with a similar half produced by the same technique. Finished mold is then ready to receive the molten metal. Blowing a liquid plastic/sand mix in a core-box also produces shell molds.

Different materials are impregnated with different plastics to provide increased performances and/or decorations. It includes application as a matrix to reinforcing fiber producing exceptionally high strength structures, saturating cement/concrete or wood to improve strength and extend environmental endurance, filling metals that are slightly porous to seal them, etc. Degree of impregnation or saturation depends on variables such as process used that includes casting, coating, extrusion, tower drying, etc. with or without vacuum in the substrate.

The trickle impregnation process is a related process to thermoset plastic casting, potting, and encapsulation where it also uses a low viscosity liquid reactive plastic to provide the trickle impregnation. As an example, the catalyzed plastic drips on to an electrical transformer coil. Capillary action draws the liquid into its openings at a rate slow enough to enable air to escape as it is displaced by the liquid. When fully impregnated, the part is exposed to heat to cure the plastic.

A variation on casting is known as liquid injection molding (LIM) and involves the proportioning, mixing, and dispensing of liquid components and directly injecting the resultant mix into a mold cavity that is clamped under pressure. In this casting process the liquid is injected under pressure that is far less than conventional injection molding (Chapters 4 and 16). A simplified view of this casting process is shown in Figure 11.1. For more precision mixing, equipment is available such as the schematic shown in Figure 11.2.

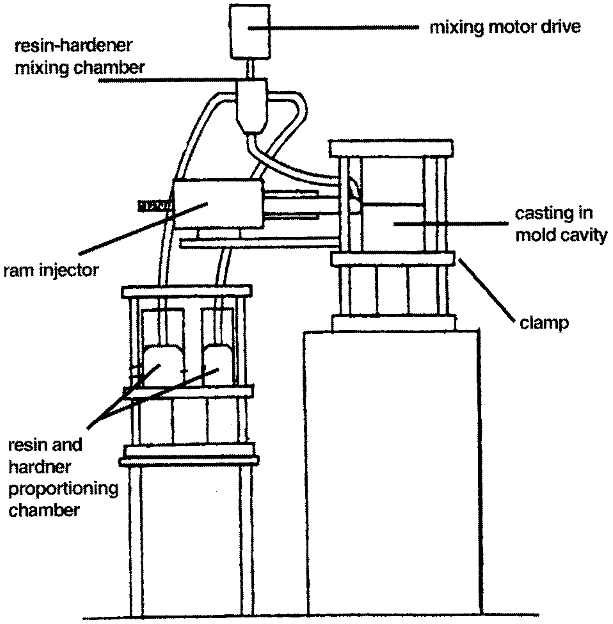

mixing motor drive
resin-hardener mixing chamber
casting in mold cavity
ram injector
clamp
resin and hardner proportioning chamber

Figure 11.1 Example of a liquid injection molding casting process

LIM can also be called reaction injection molding (RIM). This LIM process involves proportioning, mixing, and dispensing two liquid plastic formulations. This compound is directed into a closed mold. It can be used for encapsulating electrical and electronic devices, decorative ornaments, medical devices, auto parts, etc. It is different to reaction injection molding (RIM) where it uses a mechanical mixing rather than a high-pressure impingement mixer. Flushing the mix at the end of a run is easily handled automatically. Plastics used include silicones, acrylics, etc. To avoid liquid injection hardware from becoming plugged with plastics, consider using a spring-loaded pin type nozzle. The spring loading allows you to set the pressure so that it is higher than the pressure inside the extruder barrel, thus keeping the port clean and open.

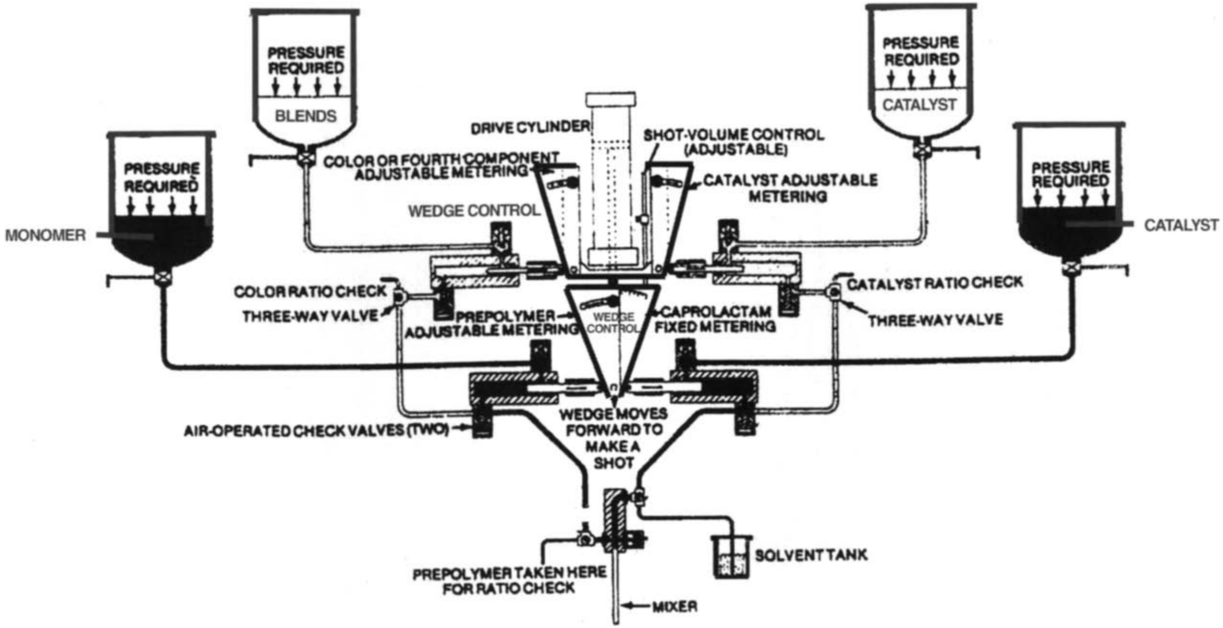

PRESSURE REQUIRED
BLENDS
PRESSURE REQUIRED
CATALYST
PRESSURE REQUIRED
MONOMER
PRESSURE REQUIRED
CATALYST
DRIVE CYLINDER
SHOT-VOLUME CONTROL (ADJUSTABLE)
COLOR OR FOURTH COMPONENT ADJUSTABLE METERING
CATALYST ADJUSTABLE METERING
WEDGE CONTROL
COLOR RATIO CHECK
THREE-WAY VALVE
PREPOLYMER ADJUSTABLE METERING
WEDGE CONTROL
CAPROLACTAM FIXED METERING
CATALYST RATIO CHECK
THREE-WAY VALVE
AIR-OPERATED CHECK VALVES (TWO)
WEDGE MOVES FORWARD TO MAKE A SHOT
SOLVENT TANK
PREPOLYMER TAKEN HERE FOR RATIO CHECK
MIXER

Figure 11.2 Example of a more accurate mixing of components for liquid injection casting

Casting of acrylic

Literature continues to be rather extensive on this subject since the 1930s. A summarization is provided in this section. Products fabricated include sheets, films, rods and tubes, and embedment. Acrylic castings usually consist of polymethyl methacrylate (PMMA) or copolymers of this ester as the major component with small amounts of other monomers to modify the properties (Chapter 2). Adding acrylates or higher methacrylates lowers the heat deflection temperature and hardness and improves thermoformability and solvent cementing capability, with some loss in resistance to weathering. Dimethacrylates or other crosslinking monomers increase the resistance to solvents and moisture.

Procedure is to pour the monomers or partially polymerized syrups into suitably designed molds and heating to complete the polymerization. A large reduction in volume, about 22%, takes place during the cure. The reaction also is accompanied by the liberation of a substantial amount of heat. At conversions above 20%, the polymerization becomes accelerated, and the rate rises rapidly until gelation occurs at about 90% conversion. Thereafter, the reaction slows down and a postcure may be needed to complete the polymerization.

During the accelerated phase, the rapid increase in viscosity and liberation of heat can raise the internal temperature and elevate the reaction rate unless measures are taken to dissipate the heat otherwise, in extreme cases, a violent runaway polymerization can occur. During this cure cycle the effects of shrinkage and interrupting the polymerization to form syrup containing 25 to 50wt% polymers can control acceleration. Syrups can be stored safely with little change until they are needed, and the amounts of shrinkage and heat production drop during the second stage of cure in accordance with the polymer content. Using syrups also shortens the time in the mold, decreases the tendency to leakage from the molds, and greatly decreases the chance of dangerous runaways.

For products needing high optical quality, syrups are produced by careful heating with precise stirring of monomer containing a small amount (0.02 to 0.1%) of a soluble free-radical initiator (peroxides, etc.) until a molasses-like consistency is achieved.

Major markets for casting sheets exist. Cast sheet is made in a batch process within a mold or cell or continuously between stainless steel belts. Basically the processing cells consist of two pieces of polished (or tempered) plate glass slightly larger in area than the finished sheet is to be. The cell is held together by spring clips that respond to the contraction of the acrylic material during the cure. The plates are separated by a flexible gasket of plasticized PVC tubing that control the thickness of the product. The cell is prepared by fitting the gasket between the plates and clamping, while leaving a corner open. The cell is tilted slightly from the horizontal and filled with a weighed amount of catalyzed syrup containing any required plasticizers, modifiers, release agents, colorants, ultraviolet absorbers, flame retardants, etc. The rest of the gasket is then set in place and clamped. The filled cell is returned to a horizontal position and moved into an oven for cure.

Thin sheet (below 0.5 in.) is cured in a forced draft oven using a programmed temperature cycle starting at about 45C and ending near 900C. The cycle is 12 to 16 hr for a 0.125 in. sheet and considerably longer for thicker sheets. Thicker sheets are best made in an oil- or water-bath or in an autoclave. Because of the poor thermal conductivity of air, the heat of polymerization in a forced draft oven can drive the temperature within the mass far above the boiling point (100C.) of acrylic. After final curing cell-cast sheet is cooled in the molds, stripped, and trimmed to size.

In the continuous casting process viscous syrup is cured between two highly polished moving stainless steel belts. Distance between the belts determines the thickness of the sheets. Width is controlled by inserting flexible gaskets between the belts and is limited only by the width of the belts. Continuous casting is less versatile than cell casting and is limited to relatively thin (up to about 0.375 in.) sheets.

An important advantage of the method is the elimination of the severe problems of handling and breakage of large sheets of costly glass that make up the cells. Cell-cast sheet has superior optical properties and light transmittance as well as smoother surfaces. The continuous process provides more uniform thickness and has less tendency to form warped sheet.

Acrylics are combustible plastics, and the fire precautions normally used with other combustibles must be observed in handling, storing, and using them. The fire hazards of acrylic installations can be kept within acceptable levels by complying with building codes, applicable Underwriters Laboratories' standards, and the established principles of Fire safety.

Sources of ignition must be kept away from these materials, and adequate, reliable ventilation and means of removing vapors must be provided in storage and processing areas. Their exists with the manufacturer of acrylic castings the situations of toxicity, flammability, and explosive potential of methyl methacrylate and peroxides. The monomer is moderately toxic in the liquid and vapor state. It can irritate the eyes and produce sensitization of the skin and give toxic or allergenic reactions in susceptible persons. Those handling the monomer or involved in cleanup of spills must wear goggles and impervious gloves and maintain strict personal cleanliness. Material safety data sheets and other information on dealing with methyl methacrylate are available from suppliers.

Casting of nylon

Monomer casting is effective for the fabrication of shaped products in practically all sizes and thicknesses. It also provides economic advantages in low or high volume manufacture. Cast parts can be either produced to size or they can be cast and then machined to strict tolerances as required in accordance with end-use needs. Monomers of the lactam family are used to make cast nylon. They will polymerize under various conditions.

Cast nylon offers advantages in applications where wear resistance, resiliency, strength, chemical and abrasion resistance, and lightness is important. Due to the higher molecular weight and crystallinity of cast nylon over that of extruded or injection molded nylon, the cast plastic possesses greater modulus, a higher heat deflection temperature, improves solvent resistance, lower moisture absorption, and better dimensional stability. In addition, the process of nylon monomer casting is more economical than extrusion or injection molding methods. Both of these processing methods are restricted to light and thin shapes compared to casting (Chapter 2). Applications include heavy-duty rotational bearings, gears, sheaves, and slide bearings. These cast nylon parts take advantage of the material's high wear resistance, strength, and lubricity. There are very large bearings of cast nylon used to reduce overall weight by many hundred pounds when substituted for bronze and other metal bearings. The energy-absorbing quality of cast nylon has reduced downtime on a transfer line of a vehicle manufacturer when used for axle pallets.

Casting nylon is a four-step process: melting the monomer, adding the catalyst and activator, mixing the melts, and casting. Optimum melt temperature must be maintained throughout the process. Lactam flakes must be melted to liquid form under controlled temperature and atmospheric humidity. Hygroscopic flake lactam must be protected from excess moisture that would cause the catalyst to decompose, preventing complete polymerization.

Solvent casting of film

While the capital equipment for solvent casting is expensive and the process considerably more complex than extrusion[167] or calendering, certain types of film can be produced that would be difficult or impossible to manufacture by any of the other film processes. In PVC, acrylic, and other plastics solvent casting film the formation depends upon solubility, not melting of the plastic. Therefore the process requires only moderate amounts of heat. PVC solvent cast film is extensively used. An example of a solvent used with PVC is tetrahydrofuran (THF). To produce PVC films by this process, the plastic, plasticizers, and other materials are added to the solvent in an inert gas-blanketed mixing tank. Thorough mixing, uniform viscosity of the solution, and thorough degassing are critical for producing a quality film. After mixing and then cooling the solution below its boiling point, it is pumped to the casting tank.

This solution is filtered to 5 microns to remove any undissolved particles and is then pumped to a specially designed flat die where the solution is cast onto a stainless steel conveyor belt. The belt then enters an oven where the solvent is evaporated from the film, the film is cooled, stripped from the belt, and wound into rolls. Control of the gauge of the film is via die opening, pumping pressure, and speed of the belt. In-line monitoring equipment is used for gauge control and for quick gauge changes. Heated air traveling counter to the direction of the conveyor belt carries the solvent vapors from the drying oven to the solvent recovery system, through large ducts.

Different designed solvent recovery systems are used. As an example there is the solvent system that consists of fixed bed adsorbers containing activated carbon and a distillation system. The carbon adsorbs the solvent vapors. Then the beds are steamed in sequence to remove the solvent. The solvent and steam are condensed into a large tank. The distillation system is then used to distill the solvent from the water to a purity of 99.99% so that it can be reused. Because of the high cost of solvent, complex monitoring equipment is used to insure a high rate of recover.

Stabilizers, plasticizers, and lubricants do not have to be added for processing since high temperatures are not required to dry the film. In addition, any polymer soluble in the solvent (THF, etc.) that will not adhere to the stainless steel belt can be alloyed with PVC or cast by itself. Typical examples include butadiene rubber, acrylic, EVA, and saran. Special PVC resins provide wide and low heat sealing ranges in rigid films. For example, an unplasticized film can be cast with a heat seal range of 250 to 340 F (121 to 193C) or a plasticized type from 180 to 240 F (82 to 116C) for use in flexible packaging laminations or for sealing to rigid vinyls.

Films made by solvent casting have sparkle and clarity, good gauge control, low strains, freedom from pinholes, uniform strength in both directions, and good optical properties. Typical applications are flexible packaging laminations for food and drugs, cap stock for scaling to rigid vinyl cups, decals, optically clear storm window film, low-temperature adhesive films, surgical drapes, and unit-dosage liquid medicine cups. Certain cast PVC films also can be processed further by tentering to provide shrink films for food and drug packaging (Chapter 5).

12 REACTION INJECTION MOLDING

Introduction

Reaction injection molding (RIM) is a relatively new manufacturing technology to produce high quality principally polyurethane thermoset plastic or thermoplastic parts; developed by Bayer in 1969. Despite its young age, this technology has become a premier plastic molding process that offers versatility in processing options and chemical systems used to produce high-quality, highly styled plastic products. Figure 12.1 provides a schematic of the typical RIM process.[263, 264, 473, 471]

RIM is a process in which two or more liquid intermediates (isocyanate and a polyol) are metered separately to a mixing head where they are combined by high-pressure impingement mixing and subsequently flow into a mold where they polymerize to form a molded part. Advantages that are inherent in the process fall into three general categories: low pressure, low temperature, and use of reactive liquid intermediate. RIM is also called reactive injection molding. If a plastic system of the RIM type is sprayed against the surface of an open mold, the expression reactive spray molding (RSM) is used.[265]

With the pressures in the mixing head at between 1,500 to 3,000 psi (10.3 to 20.6 MPa), the in-mold pressures are significantly lower than in many of the other molding processes. When comparing a typical RIM in-mold pressure of 50 to 150 psi (0.4 to 1.1 MPa) with the 5000 to 30,000 psi (34.5 to 206.7 MPa) required for thermoplastic injection molding (Chapter 4), it becomes apparent why RIM is particularly suitable for larger parts. Automotive bumpers are routinely produced on RIM presses with 100 to 150 tons of clamping force, while comparable injection molded parts require presses of 3500 tons or more.

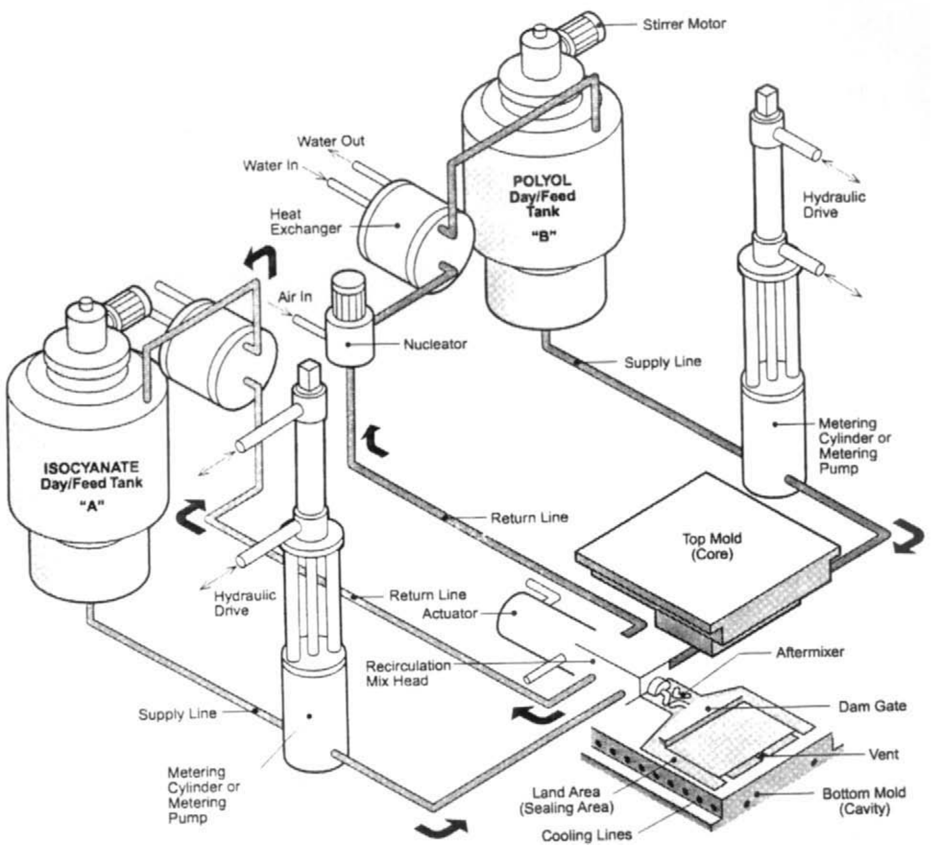

Stirrer Motor
Water Out
Water In
Heat Exchanger
POLYOL Day/Feed Tank "B"
Hydraulic Drive
Air In
Nucleator
Supply Line
ISOCYANATE Day/Feed Tank "A"
Metering Cylinder or Metering Pump
Return Line
Top Mold (Core)
Hydraulic Drive
Return Line
Actuator
Aftermixer
Recirculation Mix Head
Dam Gate
Supply Line
Vent
Metering Cylinder or Metering Pump
Land Area (Sealing Area)
Bottom Mold (Cavity)
Cooling Lines

Figure 12.1 Example of typical polyurethane RIM processes (courtesy of Bayer)

The temperatures used in RIM are also significantly lower. With polyurethanes (PURs), the intermediates normally are processed at temperatures between 75 and 120F and the mold is usually between 130 and 170F (266 to 338F). These lower temperatures obviously require significantly less energy consumption than competitive processes.

The use of liquid intermediates has additional benefits beyond the low pressures and temperatures involved. A tremendous amount of design flexibility is possible with RIM. Since the mold is filled with low viscosity liquid, very complex part configurations can be produced. Ribs, mounting bosses, slots, and cut out areas are all possible. RIM parts are being molded with wall sections as thin as 0.100 in. and as thick as 1.5 in.[1] Also, moldings can incorporate variations in thickness within the same part. Incorporation of inserts for mounting or reinforcement is also practical. Since the mold is filled before polymerization occurs, there are no molded-in stresses to cause part warping or cracking after demold.

The relative case of compounding thermoset and thermoplastic liquid formulation allows a great deal of flexibility in fine tuning the material to the requirements of the part. By changing variables such as filter type and level, blowing agent concentration, pigment, and catalyst the properties of the plastic can be optimized for the specific application.

The two major classifications for RIM products are (1) high-density, high-modulus, flexible elastomers and (2) low-density structural foams. Automotive trim and fascia are usually elastomers. Furniture and equipment housings are frequently molded as structural foams (especially when texture and/or sound deadening are included in the product specifications).

About 85wt% of the processed PUR are elastomeric. The rest is rigid, usually structural foam that has a solid skin encasing a foamed core. PURs can be used with physical blowing agents such as halocarbons (Chapter 8). Foaming is an integral part of the RIM process even for solid products because it compensates for the shrinkage that occurs during polymerization. That is why most elastomeric products also include foaming agents. This same approach is used during injection molding solid plastics; where up to 5wt% of a blowing agent is used to compensate for shrinkage.

Overall RIM has advantages over the standard low-pressure mechanical-mixing systems in that larger parts are possible, mold cycles are shorter, there is no need for mold solvent-cleaning cycles, surface finishes are improved, and rapid injection into the mold is possible. Large and thick parts can be molded using fast cycles with relatively low-cost materials. If surface coating is required the types used are coating paint, in-mold coating (Chapter 10), film, and metallic facings. Its low energy requirements with relatively low investment costs make RIM attractive. Applications are many; they include automobile bumpers, medical products, radio and TV cabinets, furniture, sporting equipment, appliances, and business-machine housings.

An example of a large medical product is a CAD polyurethane single-shot RIM molding from Thieme Corp., St. Charles, IL. It is a 12 part enclosure for a computer tomograph (CT) device. When all 12 RIM parts are assembled, the enclosure is large. Many of these parts use a reinforcing rib design by Thieme that provides support and rigidity that allows the assembled CT unit to be moved.

An appliance application for RIM is molded by the Italian molder GMP Polyurethanes S.p.A. They created a refrigerator door that is as much a fashion statement as it is functional. GMP developed a new surface finishing technique that takes advantage of the outstanding adhesion between polyurethane and film. The patented process cuts costs by eliminating the need for post-painting, while at the same time achieving an improved surface finish.

The GMP's process eliminates the use of sheet metal for the skin of the refrigerator door. In this application, the thermoplastic film forms a durable, protective outer skin with a wide choice of color options that are applied directly to the film. In addition more innovations exist apart from the film and thermoplastic interior liner, the doors consist entirely of polyurethane. GMP backs the thermoplastic film with an approximately 4 mm thick layer of the Baydur® 110 structural foam polyurethane RIM system from Bayer AG that creates a rigid, dimensionally stable outer shell with no need for sheet metal. Then, GMP fills the space between this shell and the inner liner with insulating polyurethane foam, a rigid, low-density foam. The result is a self-supporting door that satisfies all stability, thermal insulation, and surface finish requirements.

Equipment

Processing equipment consists of the material conditioning system, the high-pressure metering system, the mixing head, and the mold carrier. Since the RIM process involves a chemical reaction in the mold after the intermediates have been mixed, it is necessary, if consistent parts are to be produced, that the material delivered to the mix head be consistent from shot to shot.

The material conditioning system is designed to ensure that the materials fed to the metering pumps meet these requirements. It typically includes tanks to hold the intermediates, agitators to ensure that the material in the tanks is of homogeneous temperature, and a nucleation control system that keeps the level of dissolved gases in the polyol component at the desired level. The tanks can range in size from 15 to 150 gal or larger depending on the consumption rate. These tanks are normally automatically refilled at frequent intervals from bulk storage tanks. Jackets on the tanks as well as heat exchangers on circulating loops are used for temperature control.

The metering system takes the conditioned intermediates from the supply tanks and delivers them to the mixing head at the desired rate and pressure. There are two basic types of metering systems: high pressure axial or radial piston pumps, and lance displacement cylinders. The piston pumps are hydraulic pumps that have been modified to handle chemicals. They are capable of continuously metering at pressures up to 3500 psi (24.1 MPa). Lance pistons, which are driven by a separate hydraulic pump, displace the reactants from a high pressure metering cylinder. In addition to more precise metering, they have the capability of processing filled systems.

The mixing head contains a cylindrical mixing chamber where the intermediates are mixed by direct impingement at pressures ranging from 1500 to 3500 psi (10.3 to 24.1 MPa). It also contains a cylindrical cleaning piston that, after the shot is complete, moves forward to wipe the remaining materials out of the mixing chamber (otherwise the mixing head would have cured plastic preventing the mixing of the next shot). There is a valving mechanism to shift the material flow between recirculation back to the tank and flow into the mixing chamber. This action allows the circulating materials to reach an equilibrium at the proper temperature, pressure, and flow rate before shifting into the mixing position.

The mold carrier holds the tool in the proper orientation for molding, provides enough clamping force to overcome the in-mold pressure, opens and closes the mold, and positions the open mold in an accessible position for demolding, cleaning, and preparing the mold for the next shot (Figure 12.2). There is a wide variety of designs and sizes available.

Mold

Since the in-mold pressures in RIM are generally relatively low [50 to 150 psi (0.4 to 1.1 MPa)] a variety of tooling constructions have been used. These include machined steel or aluminum, cast aluminum or kirksite, sprayed metal or electroplated shells, and reinforced or aluminum filled epoxy (Chapter 17). With mold pressures usually below 100 psi (0.7 MPa), mold-clamp-pressure requirements can accordingly be low when compared to injection and compression molding.

Some of these constructions are relatively inexpensive when compared with other large-volume production tooling. The low viscosity liquid that fills the mold that are heated to 120 to 160F (49 to 71C) will duplicate exactly the surface of the tool. Consequently, when good surface characteristics and high tolerances are required, machined tooling has generally been the chosen route, particularly for higher volume production runs. The ability to use less costly tooling methods for prototype and for short runs, however, remains a significant advantage of the RIM process.

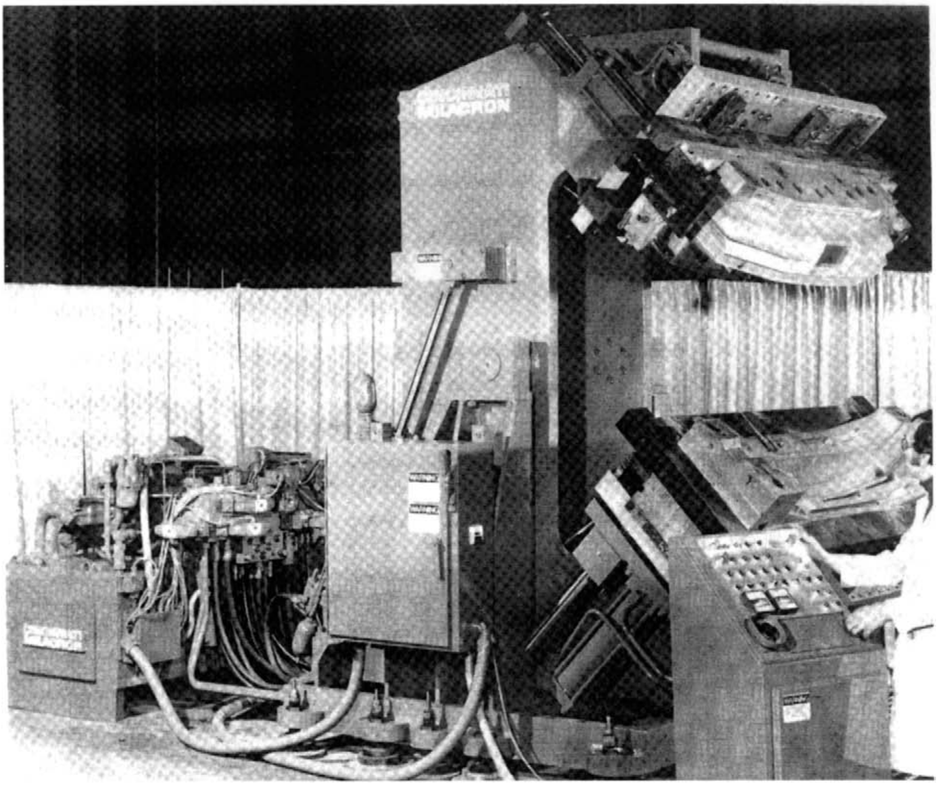


Figure 12.2 RIM machine with mold in the open position (courtesy of Milacron)

Since one of the ultimate objectives of the RIM process, for its major market of automotive exterior part production, was a cycle time of 2 minutes or less, a great deal of effort was applied to mold construction and design. Continuous automatic operation of a molding station without interruption required improvements in mold release and mold surface technology. Originally, mold preparation following a shot was required due to the buildup of external release agents, which were necessary to enable easy removal of the part from the mold.

This problem was approached from the material side, through a search for suitable internal releases, and through the development of improved external mold release compounds. From the equipment side, the development of automatic molds was required if the RIM process was to compete with classical injection molding with respect to mold cycle times and efficient production.

General Motors Corporation constructed such a mold for a production trial of the 1974 Corvette fascia (which actually started the development of RIM). This mold was tool steel with a highly polished nickel-plated surface. Most of the mold seals were elastomeric, to prevent excessive flash (up to 10%, by weight, of flash can occur; and PUR can not be reused, since a thermoset was used) due to leakage of the low-viscosity thermoset polyurethane reacting material. This was possible because of the low internal mold pressures encountered in the RIM process, less than 100 psi (0.7 MPa). This evaluation was highly successful in demonstrating the capability of total automation of the RIM process.

In the construction of molds for RIM processing, it must be kept in mind that part quality and finish are roughly equivalent to the quality and finish of the mold surface itself. A common misconception is that because the clamp tonnage for a RIM setup is relatively low, low-quality tools can be used. This, however, is true only insofar as the pressure requirements for the mold are concerned.

Experience has shown that the finish on the part surface is a direct function of the mold finish, and that the mold finish is a direct function of the quality of the mold material. Excellent results have been obtained using high-quality, nickel-plated, tool steel molds and electroformed nickel shells.

For production runs of 50,000 parts per year, a P-20, P-21, or H-13 steel would be most appropriate, not only because of these steels' homogeneous nature, but also because of their excellent polishability and adaptability for a good plating job. The prehardened grades of 30 to 44 RC are preferable because of the degree of permanency that they impart to a tool. After machining, a stress-relieving operation is very important in order to avoid possible distortions or even cracking (Chapter 17).

Nickel shells that are electroformed or vaporformed when suitably backed up and mounted in a frame are also excellent materials for large-volume runs. For activities of less than 50,000 parts per year, aluminum forgings of Alcoa grade No. 7075-T73 machines to the needed configuration will perform satisfactorily. They have the advantage of good heat conductivity, an important feature in RIM.

Cast materials are used for RIM molds with reasonable success. One such material is Kirksite, a zinc alloy casting material. Kirksite molds are easy castable, are free from porosity, will polish and plate well, and have been used with favorable results.

The mold temperature should be maintained within ±4F for consistent quality and molding cycles with PUR. The mold temperatures will range from 100 to 150F, depending on the composition being used. The cooling lines should be so placed with respect to the cavity that there is a ¾in. wall from the edge of the hole to the cavity face. The spacing between passages should be 2.5 to 3 diameters of the cooling passage opening. These dimensions apply to steel; for materials with better heat conductivity, the spacing is usually increased by one hole size.

As with the chemical components, it is necessary to maintain constant surface temperatures in the mold for a reproducible surface finish and constant chemical reactivity. This temperature varies according to the chemical system being used and has been determined empirically.

The mold orientation should be such as to allow filling from the bottom of the mold cavity, allowing escape of air through a top flange at a hidden surface. This allows controlled venting, and positioning of vent pockets that can be trimmed from the part at a later time.

Runner and Gate Design

The following Figures 12.3 to 12.5 provide an introduction to designing the RIM melt flow from the mixer into the mold cavity.[264]

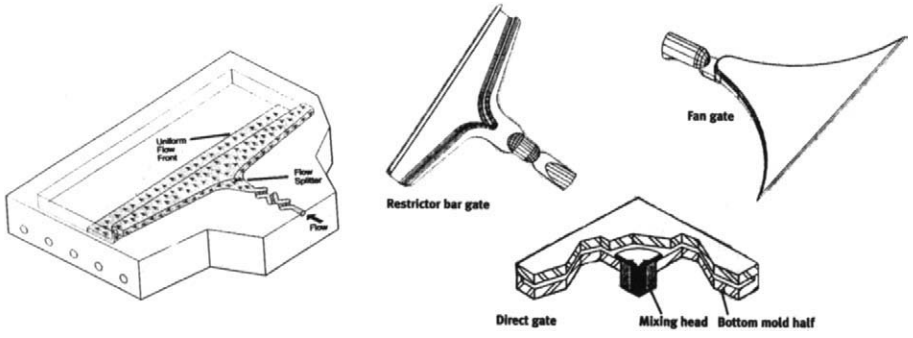


Figure 12.3 Gating and runner systems demonstrating laminar melt flow and uniform flow front (courtesy of Bayer)

Cost

Low-cost tooling is a primary benefit of RIM, especially for start-up companies and those that only need a small quantity of parts for a particular product line. Tooling costs are lower because machine pressure is much lower compared to high-pressure molding at several thousand psi, and because molds are only heated to 170F, instead of 200F or higher. Molds can be made from several different materials that offer different price ranges.[561]

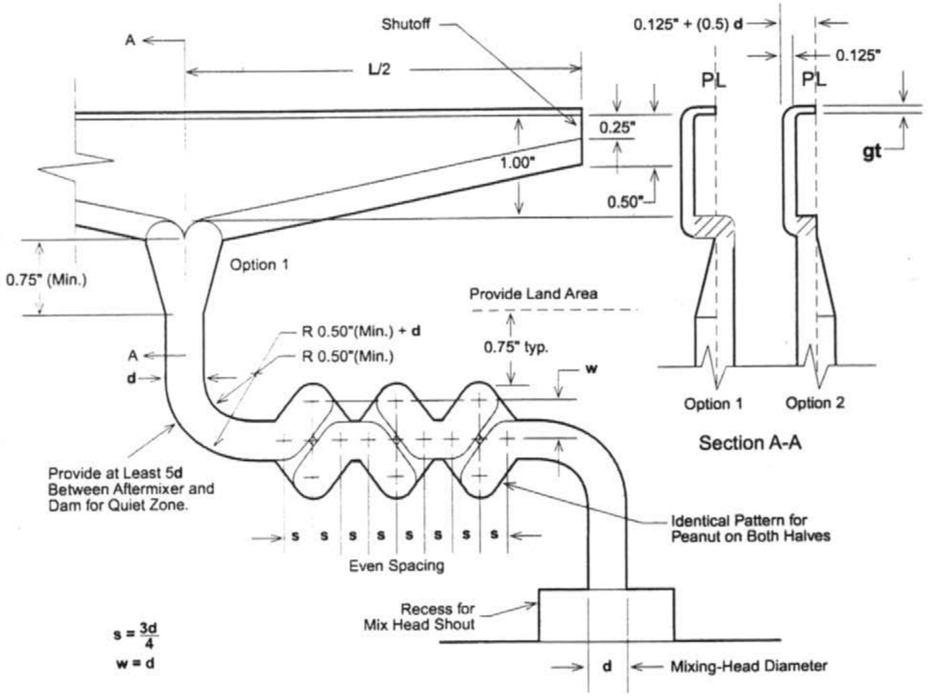

Shutoff
0.125" + (0.5) d
A
L/2
0.125"
PL
PL
0.25"
1.00"
gt
0.50"
0.75" (Min.)
Option 1
Provide Land Area
R 0.50"(Min.) + d
R 0.50"(Min.)
0.75" typ.
A
d
w
Option 1
Option 2
Section A-A
Provide at Least 5d Between Aftermixer and Dam for Quiet Zone.
Identical Pattern for Peanut on Both Halves
s s s s s s s s
Even Spacing
Recess for Mix Head Shout
s = 3d/4
w = d
d
Mixing-Head Diameter

Figure 12.4 Example of a dam gate and runner system (courtesy of Bayer)

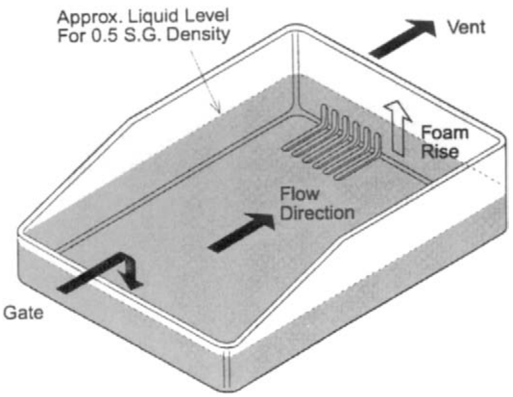

Approx. Liquid Level For 0.5 S.G. Density
Vent
Foam Rise
Flow Direction
Gate

Figure 12.5 Example of melt flow around obstructions near the vent (courtesy of Bayer)

The RIM process allows to fabricate small and large parts with equal ease. Large parts include those that are at least six feet long, four feet wide, and four feet tall, with a special holding clamp of five feet by five feet in size that is used on the molding machine. The process lends itself to reduced setup time and costs, and consequently just-in-time delivery is made easier. Machine tooling can be made out of hard epoxy, which is still very accurate tooling since it comes from CAD models,[1] or use is made of different grades of aluminum for moldmaking. Use can also be made of the softer materials and still obtain precision molds because of the low heat and low pressure required.

A disadvantage of the RIM process would be that per part costs are more expensive. However, on small runs of a few hundred parts, the lower cost of tooling far outweighs the part cost. If a customer requires several thousand parts per month, it is less costly per part to use expensive, hard steel tooling with high-pressure molding. Another downside to the RIM process is that it is limited to using a few plastics with principally polyurethane, whereas many different plastic materials can be used with high-pressure molding. However, polyurethanes are available with different material properties.

Processing

This high-pressure impingement mixing delivery of two or more liquid urethane components to a very small mixing chamber that continuously mixes and injects into a closed mold delivers at rates approaching 650 lb/min. The liquid components are heated to maintain low viscosities.

The heart of the system is the mixing chamber, where the liquid components must be thoroughly mixed without imparting turbulence. High-volume, high-pressure recirculating pumps from liquid-storage tanks accomplish continuous delivery of the components to the mold. Automatic controls are used to maintain precise flow and temperature of the plastic.

Unlike injection molding, the clamping press does not have to be close to the material source. The components can be transferred safely across the floor of the processing plant. A metering unit can accommodate as many as five mixheads or molding stations because the lapsed time for the metering shot is only a small fraction of the overall molding cycle.

A typical polyurethane RIM process involves precise metering of two liquid components under high pressure from holding vessels into the static impingement mixhead (Figure 12.1). The co-reactants are homogenized in the mixing chamber and injected into a closed mold, to which the mixhead is attached. The heat of reaction of the liquid components vaporizes the blowing agent, beginning the foaming action that completes the filling of the mold cavity.

Proper temperature control of raw material is critical for maintaining the best product characteristics. The ambient temperature in your plant during every season plays an important role when choosing the right heating and chilling equipment to maintain accurate process control of your material. It is important to know the average temperature in your plant year-round to properly size the conditioning system to the process. Most temperature conditioning systems will require a source of city or chilled water to operate the conditioning equipment. You need to make sure this source is available to the metering equipment if required.

Two streams of PUR chemicals collide with each other violently and under high pressure generally at 1,500 to 3000 psi (10.3 to 24.1 MPa) inside the mixer. When these impinging streams collide, the flow is very turbulent and the reaction begins. The stream exits the mixhead and is directed into the mold. After the pour a piston inside the mixhead scrapes the walls of the chambers completely clean so that no reacted foam is left inside the mixhead.

There is the straight-through mixhead with its straight chamber into the mold. It has been largely replaced by an L-shaped mixhead with its bent chamber. Processors usually prefer the L-shaped because there is laminar flow when the mix exits the head, and an aftermixing action can be built into the mixing head instead of into the mold (where it occurs for straight-through mixheads).

During mixing if the temperature is not properly controlled, the viscosity of the mix will change, reducing throughput, lowering efficiency, and impairing the quality of the products and perhaps even damaging them. A metering unit measures the chemicals and delivers the required amount to the mixhead. Electronics and closed-loop controllers are used for pump-type metering units. Although there are lower cost systems that can process quality PUR foam, they may not be able to upgrade as requirements increase. For example, the use of smaller tanks may limit the shot-size capability. Throughput for RIM can range from 0.25 to 30 lb/s.

The chemical system and the final molded product requirements determine machinery requirements. Features to review in specifying equipment based on requirements to produce products includes the addition of a third and fourth component coloring paste in order to mold colored products. Many machinery suppliers offer color-dosing units in conjunction with a three or four component mixing head as auxiliary equipment. Clamps come in a variety of shapes and sizes; most are custom-built. A clamp should have a smooth action through its entire operational sequence. Any error in movements can damage a mold, and improper sequencing can lead to poor production quality.

RIM elastomers as well as structural foams processed often include the dispersion of insoluble gas (air or nitrogen) in the form of small bubbles into the polyol component. This action results in nucleation. It is used to improve the flowability of chemical and to improve the cell structure of the final product. Improved flowability makes the melt flow more laminar and increases the throughput via a very fine pattern of cells all through the molded product.

Molders utilizing this system require equipment to measure and control the amount of entrained gas in the liquid at the desired level. They can include mass flow meters with density devices, nuclear density monitoring devices, as well as a variety of other densities measuring devices to control nucleation level. All these systems work within very defined pressure and temperature limits; however, outside these limits, readings become erratic. There are systems that remove the dependence on system pressure and temperature. This system provides more consistent data.

With relatively long cure times that are much longer than the duration of the molding cycle shuttles, turntables, or mold movement tracks are used as a production solution. By this type action in moving the mold, the metering unit can be used to greatest effect, optimizing the time interval between shots. Software programs are available so users can monitor and control the complete process. The software generates a graphic illustration of process parameters such as pressures, temperatures, mixture levels, mixture ratios, and output rates. Software is also available for preventive maintenance and troubleshooting.

Process Control

The chemical systems for RIM all have one characteristic in common: they require a RIM machine to convert liquid raw materials into quality plastic products. Assuming a properly formulated chemical system, the quality of the end product results from the ability to measure, control (Chapter 3), and adjust temperature, ratio, pressure, and other essential process parameters of the RIM dispensing machine. Such exacting control leads to a reduction in start-up time, minimal rejects and touch-up work, reproducible product quality, and the ability to pinpoint changes in product properties.

As an example in the high-temperature RIM processing of nylon, temperatures are monitored and controlled within ±2F using both electrical heat tracing and hot oil jacketing. The controllers contain high-low set-points; all temperature zones must be at the required settings to permit proper machine operation. A graphic diagnostic panel, with light-emitting diodes (LED), associated with all key switches, valves, and pressures, aids in troubleshooting; if a malfunction occurs, a blinking light pinpoints the cause. Low- and high-pressure circulation is monitored by transducers and displayed digitally; high/low pressure limits, if exceeded, will abort the RIM cycle for safety reasons.

Properties interact with the end product requirements such as product size, flowability through the mold and cycle times to determine necessary pressure and output requirements of the processing equipment. To begin your chemical system selection, write a performance specification for the product. Recommended formulations for specific product types have been thoroughly tested and evaluated by the chemical companies selling them. The chemical companies can provide you with the physical property data of the formulation.

All data must be carefully evaluated prior to making an educated decision about the chemical system to purchase for the production of your specific product. Rough guidelines can also be established by knowing what other types of products are manufactured with the same chemical system that you are evaluating. Compare this data to your expected results. Upon completion of a careful evaluation and selection of your chemical system, the next step is to match your process control system with your processing machinery.

Material

RIM was developed as a processing technique for polyurethane and to date the bulk of the usage has been with that material. Fortunately, polyurethanes and related plastics are a tremendously diverse group of materials with a range of properties to fill the needs of very different applications (Chapter 2).

These polyurethanes are produced by a volatile chemical reaction. Compounds containing active hydrogens, alcohols in the form of polyols, react with isocynanates in an exothermic reaction to form polyurethane. This process produces the plastic by starting with the monomer (Chapter 1).

The basic materials used are polyols and isocyanates. Polyols may be polyethers or polyesters. The isocyanates may be diphenylmethane-4,4-dioscyanate (MDI) or toluene diisocyanate (TDI). Additives such as catalysts, surfactants, and/or blowing agents are also incorporated. Their purpose is to develop the chemical reaction and form a finished product possessing the desired properties.

The high degree of reactivity of the isocyanate (NCO) group is the key to polyurethane chemistry. A urethane group is obtained by reacting the isocyanate group with an alcohol (OH) group. To obtain the polyurethane products discovered by Otto Bayer during 1937, isocyanates with two or more NCO groups must essentially be converted using compounds that likewise contain at least two OH groups (polyols).

All industrial polyurethane chemistry is based on only a few types of basic isocyanates. The most significant aromatic diisocyanates are TDI and MD. TDI is derived from toluene. This is initially nitrated to dinitrotoluene, then hydrogenated to diamine, and finally phosgenated to diisocyanate. A defined mixture of isomers comprising toluene-2,4- and 2,6-diisocyanate is obtained. Approximately 1.3 million tons/year of TDI are produced world-wide, most of which is used in the production of polyurethane flexible foam materials.

TDI production has long since been over-taken by that of diphenylmethane-4,4′-diisocyanate (MDI), which is currently running at about 2.3 million tons/year. The abbreviation MDI is derived from the former name methylene diphenyidilsocyanate. MDI is produced by phosgenation of the diamine MDA, which is obtained from benzene using nitrobenzene and aniline and by condensing using formaldehyde. The actual diphenylmethane-4,4″-diiso-cyanate (MDI) is then distilled out from the raw phosgenated product which is extensively present as a mixture of isomers and homologues. It is primarily used for polyurethane elastomers. The main quantity remains a mixture of compounds with 2 or more aromatic rings, and is known as polymeric MDI (PMDI).

Polyurethane rigid structural foam was one of the earliest applications for RIM. Lightweight and rigidity characterize the material. It consists of a solid skin and a lower density cellular core. Use includes equipment housings, furniture, building components, fancy tires,[266] and a variety of industrial and consumer applications (Table 12.1).

Low modulus elastomers are materials that have found wide use in the automobile industry for fascia, bumper covers, and trim parts. Other applications include integral window seals and a wide variety of applications where it is replacing molded rubber. Most of these materials are not pure polyurethane, but polyurethane/polyurea hybrids with improved processing and properties when compared with the earlier all-urethane systems.

Table 12.1 Comparing processes to mold large, complex products

PROCESS	DESIGN FLEXIBILITY	STRUCTURAL INTEGRITY	SECONDARY OPERATIONS	RELATIVE TOOLING COST	ASSEMBLY FLEXIBILITY
Reaction injectin molding	Good design flexibility due to low pressures but large complex structural parts not feasible due to lower material properties Thicker sections required Batch process	Lower properties can prohibit complex high-stressed features Lower impact and creep resistance	Flashing must be trimmed	Low tooling cost	Thermoset process such that thermal fastening techniques not possible
Injection molding	some flexibility possible, but due to high pressures, large complex parts not cost effective Ribs required for high load-bearing parts Sink marks in thick sections	Good structural integrity	Sprue removal Class A finish	Higher pressures req. expensive steel tools: high-strength, prehardened	In thermoplastics, vibration welding, ultrasonic bonding, self-tapping screws, ultrasonic inserts and adhesive bonding possible Parts can be consolidated
Sheet molding compound	Fiber orientation and resin-rich areas may occur in complex, load-bearing areas Lower fatigue strength limits complex, dynamic parts Limited deep draws on complex/large surfaces	Possible nonuniform physical properties Lower impact strength	Deflashing Large or small openings must be trimmed or cut out	Steel tools required	Thermoset materials: requires molded-in inserts
Structural foam molding	Due to low pressures, significant design flexibility possible (parts consolidation, etc.) High rigidity allows for high load-bearing structural members No sink marks with integral function	Good structural integrity Low-molded-in stress provides low warp, dimensionally stable parts	Sprue removal Painting req. for appearance surfaces	Lower tooling cost; aluminum tools possible	Vibration welding, ultrasonic bonding, self-tapping screws, ultrasonic inserts, adhesive bonding possible Many parts can be integrally molded
Die casting	Limited complex-part capability Large parts are heavier	Good structural integrity Lower impact strength	Trim dies required Machining of critical surfaces	High tooling cost tool maintenance required due to potential wear damage	Hardware assembly
Sheet metal	Only simple shapes and contours possible Requires multiple dies for part complexity Inferior dimensional control	Minimal integral component strength due to multiple component assembly	Multiple assembly operations: drilling, tapping, welding	Low cost tooling Complex deep-draw dies etc. High piece part cost	Screws, nuts, bolts, rivets, welding Parts consolidation nearly impossible

There are also the high modulus elastomers. Modifications to the chemistry of producing the low modulus elastomers allow for the processing of tough polymers with flexural modulus as high as 250,000 psi (1,723 MPa). These are used in a variety of large industrial and consumer parts.

Use is made of integral skin foams. They are flexible urethane foams with a high density skin. They are used in applications such as steering wheels, arm rests, and protective covers that must combine a tough surface and a soft feel.

One of the leading materials for automotive body panels are the all-polyurea systems which have improved high temperature stability. Very fast reactivity and rapid cycle times characterize these systems.

Heavy trucks and farm tractors are using RIM parts made with poly-dicyclopentadiene (P-DCPD). This material went from industrial applications to heavy-vehicle exterior components competing with fiber glass reinforced polyester (FRP) (Chapter 15) and aluminum. The big breakthrough in the heavy truck arena came in 1996 with the Kenworth T2000 18-wheeler, which had 14 exterior components of P-DCPD varying in size from an 80 lb roof fairing to smaller parts of 10 to 15 lb each. In the past couple of years P-DCPD RIM has made its mark in the hood of Class 8 heavy trucks.

The first P-DCPD hood appeared in 2001 on the model 9900 from Navistar's International Truck and Engine Corp. in Warrenville, IL. Currently the most prestigious application for P-DCPD is the hood on the new top-of-the-line W900L model from Kenworth Truck Co. which replaced a spray-up FRP at no additional cost and with an 84 lb weight saving. Although P-DCIPD has a lower tensile modulus than FRP, it is more flexible and better resists impact damage.[564]

Reinforced RIM (RRIM) elastomers are used. By the addition of reinforcing fillers such as milled glass fiber, glass flake, or mineral fillers in the polyurethane or short to long glass fiber in preforms, fabric, or mat forms placed in the mold cavity, the properties of the material can be altered to meet high performance requirements of the part (Chapter 15). The reinforced elastomers are used to increase flexural modulus, improve thermal properties, and improve dimensional stability.[267]

A probable first commercial use of a soy-based formulation in a high density structural foam polyurethane RIM system is from John Deere, Bayer, and G.I. Plastek, organizations that launched a commercial program during 2001. Beginning with the 2002 model year, John Deere Harvester Works' entire line of combines included body panels molded with HarvestForm™ composite.

This durable, new composite is extremely strong, and yet it weighs 25% less than steel. Some HarvestForm panels will utilize Bayer's Baydur® structural foam polyurethane RIM system, which utilizes a soybean-based polyol component. This structural foam PUR RIM formulation is based on soybeans that would produce physical properties and processing parameters equivalent to Bayer's conventional formulations.

One of the parts molded by G.I. Plastek using the soy-based Baydur material is the approximately 6 ft by 6 ft, 75 lb rear wall of the John Deere STS combine. G.I. Plastek adapted its proprietary ProTek™ in-mold coating system to the new material so that John Deere could continue to enjoy the benefits of this cost-saving alternative to painting.

There are other proprietary systems such as polyacrylamate. It is Ashland Chemical's Airmax that is designed for use with preforms or glass mats. These reinforced plastics possess high flexural modulus, good impact resistance, and high temperature stability. Systems with similar performance from isocyanate-based polymers are also used.

There are RIM systems based on chemistry unrelated to polyurethanes that are not in significant commercial production compared to the polyurethanes. Development work has taken place with materials such as nylon. The nylon RIM material is based on caprolactam. Nylon RIM polymers offer high toughness and abrasion resistance. Polydicyclopentadiene is a proprietary thermoset polymer developed by Hercules. PCPD offers high-impact resistance and stiffness. It is used in the production of snowmobile components. Other polymers are used such as epoxies, polyesters, acrylics, phenolics, and styrenics.

Almost no other plastic has the range of properties of PUR. Modulus of elasticity range in bending is 200 to 1,400 MPa (29,000 to 203,000 psi) and heat resistance from 90 to over 200C (122 to over 392F). The higher values are for chopped glass-fiber-reinforced added to the polyol blend produces RIM (RRIM). The higher performance is obtained by injecting the polyol mix into a cavity with longer fiber constructions which produces structural RIM (SRIM).

Conversion Process

In reaction injection molding, the starting point for the conversion process is liquid chemical components (monomers, not polymers). These components are metered out in proper ratio, mixed, and injected into a mold where the finished product is formed. In reality, it is a chemical and molding operation combined into one system of molding in which the raw material is not a prepared compound but chemical ingredients that will form a compound when molded into a finished part. The chemicals are highly catalyzed to induce extremely fast reaction rates. The materials that lend themselves to the process are urethane, epoxy, polyester, and others that can be formulated to meet the process requirement. The system is composed of the following elements:

1 Chemical components that can be combined to produce a material of desired physical and environmental properties. Normally, this formulation consists of two liquid chemical components that have suitable additives and are supplied to the processor by chemical companies (three or more are also used).

2 A chemical processing setup, which stores, meters, and mixes the components ready for introduction into the mold.

3 To facilitate smooth continuous operation, a molding arrangement consisting of a mold, mold-release application system, and stripping accessories.

The success of the overall operation will depend on the processor's knowledge of:

1 the chemistry of the two components and how to keep them in good working order;

2 how to keep the chemical adjunct in proper functioning condition so that the mixture entering the mold will produce the expected result; and

3 mold design as well as the application of auxiliary facilities that will bring about ease of product removal and mold functioning within a reasonable cycle (such as 1 or 2 minutes).

The production of polyurethane involves the controlled polymerization of an isocyanate, a long-chain-backbone polyol and a shorter-chain extender or cross-linker. The reaction rates can be controlled through the use of specific catalyst compounds, well known in the industry, to provide sufficient time to pour or otherwise transfer the mix and to cure the polymer sufficiently to allow handling of the freshly demolded part. The use of blowing agents allows the formation of a definite cellular core (thus the term "microcellular elastomer") as well as a non-porous skin, producing an integral sandwich-type cross section.

In RIM, all necessary reactive ingredients are contained in two liquid components: an isocyanate component and a resin component. The choice of isocyanate, as well as variations within isocyanate families, exerts a profound effect on the processing and final properties of the plastic. The chemical structures of two of the major diisocyanate types, 4,4′ diphenyl methane diisocyanate (MDI) and toluene diisocyanate (TDI), is commonly supplied in an 80/20 mixture of the 2,4 and 2,6 isomers. Early in the development of RIM systems, the MDI family was chosen over TDI, based on the following considerations:

1 *Reactivity*: Given the same set of co-reactants, MDI and MDI types are more reactive than TDI. This can be used to advantage when short cycles are required.

2 *Available co-reactants*: The high reactivity of the MDI types also makes available a larger number of co-reactants. For example, where hindered aromatic amines yield a given level of reactivity, a variety of glycols can give equivalent reactivity thus allowing more formulation versatility.

3 *Handling*: The MDI materials offer excellent handling characteristics due to comparatively low vapor pressure.

4 *Green strength*: The ortho-isocyanate groups of TDI are less reactive than the para-groups. Thus, at the end of the reaction to form a polymer, the rate of reaction slows, resulting in green strength problems upon demolding. MDI does not suffer this deficiency.

As reviewed, reaction injection molding involves very accurate mixing and metering of two highly catalyzed liquid urethane components, polyol and isocyanate. The polyol component contains the polyether backbone, a chain extender or crosslinking agent, and a catalyst. A blowing agent is generally included in either the polyol or isocyanate component.

In order to achieve the optimum in physical properties and part appearance, instantaneous and homogeneous mixing is necessary. Insufficient mixing and/or lead/lag results either in surface defects on the part or, at the time of postcure, delamination or blistering.

The urethane liquid components are stored at a constant temperature in a dry air or nitrogen environment. These components are delivered to high-pressure metering pumps or cylinders that dispense the respective materials at high pressure and accurate ratios to a mixing head. The materials are mixed by stream impingement. Additional mixing is generally encouraged via a static mixer (tortuous material path) incorporated into the runner system of the mold. Following the injection of the chemicals, the blowing agent expands the material to fill the mold.

The preferred route for high-volume RIM manufacturing is multiple clamps fed from a single metering pumping unit, the logic being that this is the most efficient way to utilize the capacity of the mold-filling equipment.

Thermoplastic Polyurethane

The first polyurethanes to become commercial in 1937 by IG Farbenindustrie (later became Bayer AG) was a thermoplastic (TP). It was targeted to improve the properties of nylon. TP polyurethanes are plastics that, after processing via heat and cooling into parts, are capable of being repeatedly softened by reheating.

Thermoset Polyurethane

These thermoset (TS) plastics, after final processing into products, are substantially infusible and insoluble. They undergo a chemical reaction (crosslinking) by the action of heat and pressure, oxidation, radiation, and/or other means often in the presence of curing agents and catalysts. Curing actually occurs via polymerization and/or crosslinking. Cured TSs can not be resoftened by heat. However, they can be granulated with the material being used as filler in TSs as well as TPs.

Cure of Thermoset

Ideally thermoset plastics should combine (1) low molecular weight during processing, to provide easy melt fluidity; and (2) infinite molecular weight in the end-product, to provide maximum end-use properties. The organic polymer chemist has myriad functional groups and reactions to produce this paradoxical combination of properties with many of them in commercial use. Before considering them individually, however, it is best to start by noting that the molding of thermoset plastics has encountered a number of practical difficulties that have limited the rate of growth of this technology. These difficulties are based on conflicting requirements.

The process engineer would like materials that have unlimited shelf life (warehouse storage before use), pot life (working time after the reactive components are mixed), and process working time in general (resistance to premature crosslinking between cycles, in dead spots, and during down time). In fact, ideally, one would like a one-part system, which means that a mixture of all the reactants would be stable indefinitely. All these requirements spell low reactivity.

On the other hand, once one has melt flowing into the mold, one would like the fastest possible reaction to produce final cure and a short process cycle for maximum process economy. This clearly means high reactivity.

Considering the total irreconcilability of these two conflicting demands, it is remarkable how far the ingenuity of organic polymer chemists has gone towards producing some reasonable compromises, and the range of balance in these compromises has increasingly diversified with general progress in the field. A variety of techniques are used:

1 Mixing of reactants as they are injected into the mold has been most highly developed in RIM technology.

2 Thermal activation can combine stability at low temperature with high reactivity at high temperature.

3 Mixtures of solids are stable at room temperature, but melt and cure rapidly at molding temperature.

4 Microencapsulation of the catalyst or curing agent can produce a stable one-part system that is activated by crushing or melting of the encapsulant during molding.

5 Latent catalysts are stable at room temperature, but are liberated or otherwise activated at molding temperature.

6 "Blocked" reactants are stable at room temperature; at molding temperature they "unblock," liberating the reactant to permit cure. This is most commonly practiced in urethane.

A third difficulty in many thermoset systems is due to the fact that they are condensation reactions, which liberate gases, or volatile liquids that must be vented to permit production of solid flaw-free parts. Venting is an established practice in molding of thermosets.

Despite these difficulties, nearly all-conventional thermoset plastics are potentially adaptable to molding.

Polymerization

Polymerization is basically the bonding of two or more monomers to produce polymers/plastics (Chapter 1). A chemical reaction, addition or condensation, in which the molecules of a monomer are linked together to form large molecules whose molecular weight is a multiple of that of the original substance result in high molecular weight components.

RRIM and Resin Transfer Molding

The mold in RRIM is similar to resin transfer molding (RTM) (Chapter 15). In the reinforced RIM (RRIM) process reinforcements such as woven or nonwoven fabrics, short glass fibers, glass flakes, milled fibers dry reinforcement preform, etc. are placed in a closed mold. Next a reactive plastic system is mixed under high pressure in a specially designed mixing head. Upon mixing, the reacting liquid flows at low pressure through a runner system to fill the mold cavity, impregnating the reinforcement in the process. Once the mold cavity is filled, the plastic quickly completes its reaction. The complete cycle time required to produce a molded thick product can be as little as one minute.

These reinforcements provide stiffening or strengthening to the product and reduce thermal expansion. The usual procedure is to layout reinforcement in the mold cavity using some type of clamping system prior to the reaction injection molding process occuring. With milled fibers (glass, etc.), they can be mixed into one of the liquid reactive material tanks where a continuous stirring action exists.

As reviewed, an advantage of RRIM is its low mold cavity pressure that usually ranges from 50 to 150 psi (0.4 to 1.1 MPa) compared to the higher pressures of resin transfer molding, compression molding, and injection molding. RRIM can use preforms that are less complex in construction and lower in reinforcement content than those used in RTM. The RRIM plastic systems available will build up viscosity rapidly, resulting in a higher average viscosity during mold filling. This action follows the initial filling with a low-viscosity plastic.[263]

13 ROTATIONAL MOLDING

Introduction

Rotational molding (RM) is also called rotomolding, rotational casting, centrifugal casting, or co-rotational molding. This method, like blow molding (Chapter 6) and thermoforming (Chapter 7), is used to make hollow thermoplastic one-piece products (Table 13.1). Products include many different types such as furniture, light shades, marine accessories, material handling bins, shipping drums, storage tanks and receptacles, surf boards, toys, and so on. Sizes range from small balls to at least 22,000 gallon tanks (83 m^3) that weigh at least 2½ tons (5500 lb). Process is based on the heating and cooling of an axially or biaxially rotating split hollow cavity mold that defines the outside shape of the required product. No pressure is applied other than the relatively low-contact pressure developed during rotation of the heated melt. The most common is the multi-arm turret machine that has a three-stage operation.[265, 268–275, 477]

A measured amount of powder or liquid thermoplastic (TP) is placed in the cavity that is mounted on a turret arm capable of rotating the mold. The mold in the oven spins biaxially with rotational speeds being infinitely variable, usually ranging up to 50 rpm on the minor axes and 12 rpm on the major axes. A 4:1 rotation ratio generally is used for symmetrically shaped parts. A wide variety of ratios are necessary for molding unusual and complex shapes.

This mold action permits uniform distribution of the plastics that is forced against the inside surface of the cavity. Following a prescribed cycle, the heat of the oven fuses or sinters the plastic and goes into the cooling chamber. The solidified product is removed from the mold and the cycle is repeated. This process permits molding very small to very large products. To improve product properties, hasten product densification, reduce air voids, reduce cure time, etc.

Table 13.1 Comparison of different processes

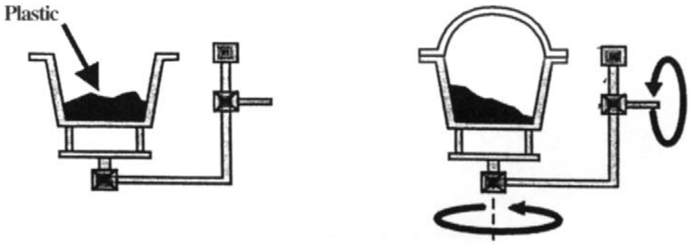
Elements	Rotational Molding	Blow Molding	Thermo Forming
Typical product volume range (cm^3)	10^1–10^8	10^1–10^6	5×10^0–5×10^6
Orientation in part	none	high	very high
Residual stress	low	moderate	high
Part detailing	ok	very good	good, with pressure
In-mold graphics	yes	yes	possible
Cycle time	slow	fast	fast
Labor intensive	yes	no	moderate
Plastics available	limited	limited	broad
Feedstock	powder/liquid	pellets	sheet
Raw material preparation cost	up to 100%	none	up to +100%
Reinforcing fibers	yes,	yes	yes
Mold materials	steel/ aluminum	steel/ aluminum	aluminum
Mold pressure	<0.1 MPa	<1 MPa	<0.3 MPa
Mold cost	moderate	high	moderate
Wall thickness tolerance	10%–20%	10%–20%	10%–20%
Wall thickness uniformity	uniformity nonuniform	tends to be nonuniform	tends to be nonuniform
Inserts	yes	feasible	no

The cycle times typically range from 3 to 15 minutes. However they can be at least 30 minutes for large and thick products. The wall thickness of the parts affects cycle times, but not in a direct ratio. As an example, with polyethylene plastic the cycle time increases by about 30 s for every 25 mils of added thickness up to ¼ in. thickness. Beyond ¼ in. the heat insulating effect of the walls increases cycle times disproportional for any further increase in thickness; cycle times usually have to be determined experimentally and/or with prior experience.

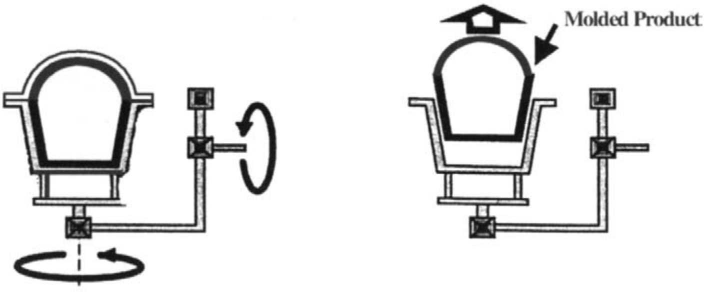
Venting molds are often used to maintain atmospheric pressure inside the closed mold during the entire molding cycle. A vent will reduce flash and prevent mold distortion as well as lowering the pressure needed in the mold to keep the mold closed. It will prevent blowouts caused by pressure and permit use of thinner molds. As an example the vent can be a thin-walled plastic tube of PTFE that extends to near the center of the cavity. It enters the mold at a point where the opening it leaves will not effect the parts' appearance, etc. The vent can be filled with glass wool to keep the powder charge from entering the vent during rotation.

Process

There is basically a three step rotational molding (RM) process where the heating and cooling cycles are in the same location. Figure 13.1 shows a four-step rotational molding (RM) process where heating and cooling are separate steps. This cycle starts with charging a measured amount of plastic (basically the weight of the solidified molded product) into a mold that is rotated at relatively low speeds in usually a gas, electric, or flame fed oven about two axes perpendicular to each other. The oven's heat penetrates the mold, causing the plastic that is usually in solid form to become tacky and adhere to the mold female cavity surface. When using solid pellets they are required to be rather smaller and more uniform than the type used in other processes such as injection molding or extrusion. With a liquid plastic the heat forms a gel on the mold surface.



(1) Charging (2) Heating



(3) Cooling (4) Demolding

Figure 13.1 Rotational molding's four basic stations (courtesy of The Queen's University, Belfast)

Since the mold continues to rotate while the heating continues, the plastic will gradually become distributed relatively evenly on the mold female cavity walls through gravitational, mold rotating, force. Gradually the plastic completely melts forming a homogeneous layer of molten plastic. Following the heating step is cooling the mold. With the mold continuing its rotation, cooling is usually done by air from a high-velocity fan and/or by a fine water spray over the mold. After cooling the plastic melt the mold is opened and the solidified product is removed manually or automatically.

RM molding pressure and temperatures are unique compared to most other manufacturing processes because there is no mechanical/pressure shearing heat used to melt the plastic; it's a takeoff of casting plastic (Chapter 11). This process relies on convection heat through the mold to melt the plastic. Each plastic used has its required melting temperature (Chapter 1). Non uniform heat on the mold's female cavity or over heating to reduce cycle time can damaging the plastic. Accuracy of controlling temperatures requires sensors proper located for proper monitoring. If these variables exist it can become extremely difficult to repeat processing conditions (Chapter 3).

Molding machines usually have horizontal rotating arms with closed, recirculating, high-velocity, hot air ovens, with total automation of the complete process. Many of these machines are computer programmed to obtain consistent product quality. The mold in the oven rotates biaxially with rotational speeds being infinitely variable. A 4:1 rotation ratio generally is used for symmetrically shaped parts. A wide variety of ratios are necessary for molding complex shapes such as a boat (Figure 13.2). Actual ratio relates to the melt flow characteristics of the plastic being processed.

Plastic

Nearly all BM products are made from thermoplastics although thermoset plastics can be used. Linear low-density polyethylene (LLDPE) is the major plastic used with 85wt% of all plastics representing different forms of polyethylenes.[271] Other plastics include nylon, polycarbonate, TP polyester, and polypropylene. In addition to the usual solid plastic products, these plastics can also be foamed (Chapter 8). Table 13.2 and Figure 13.3 provide examples of RM products that range from polyethylene small beach ball to cross-linked polyethylene (XLPE) 22,500 gallon large tank. This size tank with 1½in. wall thickness uses a triple XLPE charge with the first about a 2,500 lb charge, and the following two each at 1,500 lb (Chapter 1).

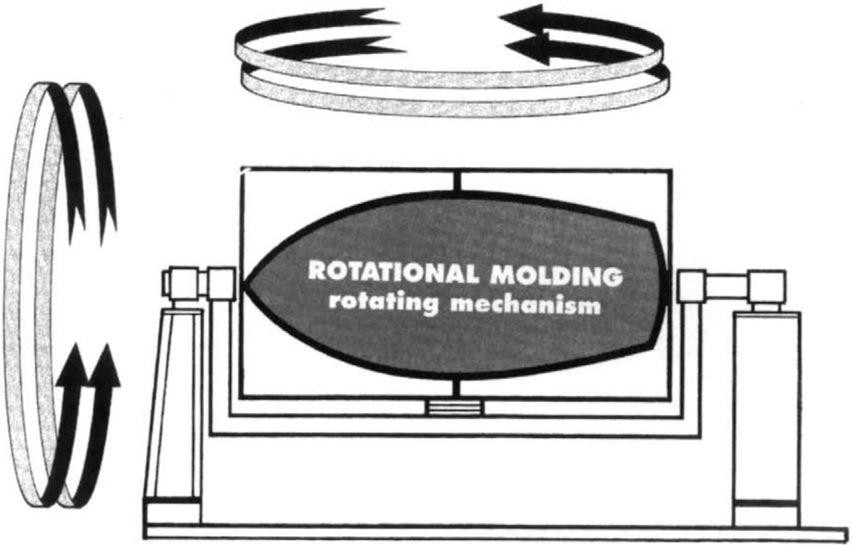


Figure 13.2 Rotational rate of the two axes is at 7:1 for this product (courtesy of Plastics FALLO)

Table 13.2 Examples of RM products

Tanks		
Septic tanks	Industrial tanks	Chemical storage tanks
Oil tanks	Nonplastic tank liner	Fuel tanks
Water treatment tanks	Agricultural equipment	Shipping tanks
Automotive		
Door armrests	Bumper	Ducting
Traffic signs/barriers	External 3-D panels	Wheel arches
Fuel tanks	Instrument panels	
Containers		
Reusable shipping containers	Planters	
Airline containers	Refuse containers	
Drums/barrels	Refrigerated boxes	
Toys and Leisure		
Playhouses	Outdoor furniture	Sporting goods
Balls	Hobby horses	
Ride-on toys	Doll heads and body parts	
Materials Handling		
Pallets	Storage bins	Fish bins
Trash cans	Skids	Packaging
Carrying cases for paramedics		
Marine Industry		
Dock floats	Leisure craft/boats	
Pool liners	Kayaks	
Docking fenders	Life belts	
Miscellaneous		
Manhole covers	Consumer products	Tool boxes
Housings for cleaning equipment	Lawn equipment	Dental chairs
Point-of-sale advertising	Garden equipment	

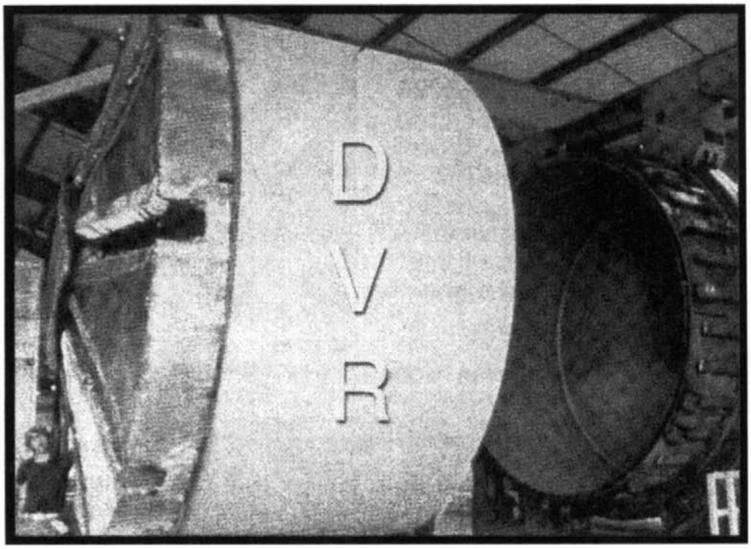


Figure 13.3 Example of large tank that is RM

Plastic powder form used usually has a particle size of 35 mesh (74 to 2000 µm). The particle size of powders is usually quantified in terms of the mesh size. This relates to the number of mesh openings per inch in the sieve used to grade the powder that are defined in industry mesh size standards.

Some high-flow plastics, such as nylon, have been used in small pellet form. Ethylene vinyl acetate and PEs are also used in specialized applications as are PVC, PC, TP polyester, nylon, and PP. RM vinyl plastisols produce different products such as beach balls, floating animals, and toys as well as industrial products. The liquid or powdered plastic used in this method flows freely into comers or other deep draws upon the mold's being rotated and is then fused by heat passing through the mold's wall.

The plastics used in RM are generally more expensive than the pelleted plastics used in many other processes because they must be more finely and evenly powdered. A degree of compensation on plastic used in RM exists. The process generates low or no levels of regrind or scrap, even when it is operating inefficiently. With properly designed molds products can have no flash.

The molding of two or more different types of plastics in a single product may be accomplished to combine their specific properties and/or a better performing or lower-cost product. This process, called corotation, is similar to coinjection or coextrusion in terms of the performance of the designed product (Chapters 4 and 5).

While RM has many advantages such as low mold costs, seamless, stress-free moldings, controlled wall thickness distribution, etc, it is characterized by no shear during shaping and slow cooling rates. These two factors lead to unique structural features in RM products. The absence of shear does not encourage good mixing of additives such as pigments, and the slow cooling promotes large spherulitic growth. Also the longer cycle times and the presence of oxygen at the inner free surface of the moldings means that degradation processes can be initiated very quickly if the correct molding conditions are not used.

Plastic behavior

RM has features which contribute to the microstructure of the molded plastic product. With slow speeds the melt has low shear that develops textures that are free from orientation. However it prevents the dispersion additives like pigments. If the heating of the plastic is too excessive its degradation may occur at the inner free surface causing spherulites that grow freely at that surface to be replaced by a non-spherulitic or a transcrystalline texture depending on the extent of degradation (spherulites are rounded aggregate of radiating lamellar crystals). The plastic microstructure in the bulk, and also at the inner surface layer has a major influence on the mechanical properties of the molded material.

Regular and crosslinked polyethylene (PE) and polypropylene (PP) have an effect or influence the RM process such as molding temperature, grinding and mixing conditions, type and level of additive (pigment, anti-oxidant, etc.), mold material of construction, and inner atmosphere.[272] As an example the use of increased amounts of antioxidant in the plastic, or the use of an inert atmosphere, delays the degradation but does not prevent it.

Performance

The rigidity or flexibility of the molded product is controlled by the formulation of the plastic used, by the wall thickness, and shape. With increased melt temperature of LDPE decrease occurs in chemical resistance, ductility, impact strength, tensile strength, modulus of elasticity, and weatherability.

Examples of product advantages include seamless, stress-free, short lead-time for the manufacture of mold, one or more cavities in a mold can process same or different plastics, corotation of plastics including recycled plastic, and plastic foam. The dissimilar molding powders that have different softening/melt temperatures can be molded simultaneously or separately, depending on the processing conditions and the end product's requirements.

Machine

Construction of machines meet different requirements based on type product to be molded. There are the batch and the most common carousel types. Batch type is manually operated going into an oven followed with the cooling station. The carousel type with basically its three- or four-station includes a loading, heating, cooling, and product removal station. Three cantilever arms 120° apart are used on a central turret so that as one arm with a mold leaves a station, another follows into that station. All operations are automatically operating. The four-arm machines can provide a second oven, cooler, or load station, depending on which is the most time consuming so that the cycle time can be reduced.

There is double–axis rotation, carousel, shuttle, clamshell, rock-and-roll machines, and so on. These designs are similar to other molding systems whereby multiple molds can be used to speed up or even simplify production. Double-axis RM uses two platforms to hold molds. The carousel types can have three to six arms for mounting molds.

Shuttle machines are desired for RM of large products such as tanks (Figure 13.4). A frame for holding one mold is mounted on a movable table. The table is on a tract that allows the mold and the table to move into and out of the oven. After the heating period is complete, the mold is moved into an open cooling station. A duplicate table with a mold moves into the heating oven, usually from the opposite side of the oven. As one mold is being cooled, the other mold is in the heating stage, and so on.

A high productive high-speed shuttle machine is used that provides advantages such as using 50% or less floor space, It combines the configuration of an inline shuttle system with a rocking oven design in a single machine. The linear platform, oscillating oven technology, and multiple (3 or 4) independent heating zones all contribute to operating efficiency.

The clamshell machines have only one arm. The same location provides mold loading, heating, cooling, and unloading. It uses an enclosed oven that also serves as the cooling station.

The rock-and-roll (slush) equipment is used for molding products with relatively long shapes such as canoes, surfboards, open-ended containers, shoes, etc. It rotates on one axis and tilts to provide action in the other axial direction. Most of the motion is in the long direction of the product, which relates to the main rotating motion. They basically rotate only on one axis, fabricating. The material moves back and forth (slushing action) during the heating cycle.

RM machines are becoming larger and more electronically sophisticated. Larger machines generally require more sophisticated electronics to provide increasingly precise control of the molding process.[274]

Microprocessors that control processing improve the precision of the product (Chapter 3). It optimizes the process by controlling the machine cycle based on temperature and time, rather than time alone by using an infrared thermometer to monitor the mold's outer temperature. The molding cycle data for the oven and cooling chambers can be stored for different products and recalled when needed. Cycle time, oven temperature, major and minor axis speeds, fan and water spray times are typical of functions under complete computer control.

Arms can be equipped with inner lines capable of bringing hot air, nitrogen, or vacuum into a mold during the heating cycle. The same lines can bring pressurized air into the mold during the cooling cycle. There is also special machines developed such as in Australia that deviates from the use of a traditional oven. This type of machine uses conductive composite mold rotating biaxially on a frame to form products without using an oven or open flame.

There are systems that precisely dispense up to four material components into a mold. The plastic is dispensed up to 6 lb/sec with a reported accuracy of ±0.02 lb. The system works as the feeder automatically reads a barcode. The barcode is matched to a dispensing recipe and then the required amounts of color and plastic powder are dispensed. The system is capable of holding more than 65,000 recipes.

Mold

Most molds are thin shell-like structures made from metals. Molds made from other materials (plaster casting, reinforced plastics, wood, etc.) are used for special applications. Lightweight cast aluminum and electroformed or vaporformed nickel molds, which are light in weight and low in cost, can be used. Aluminum molds are very popular especially for small to medium-size products. Aluminum has better heat transfer than steel and is very cost-effective when several molds for the same product are required. The aluminum mold with good framing is frequently a good choice for structural products, as it can easily be constructed to allow contoured shapes. Sheet metal molds can be used for larger products. They are easy to produce since sections can be welded together. Since the molds are not subjected to pressure during molding, they are not built to take the high loads required in molds for injection, compression, and other pressure operating molds (Chapter 17).

Two-part molds are usually used but molds in three or more parts are sometimes required to remove the finished complex shaped products. Molds can be as simple as a sphere, and molds can be complex with undercuts, ribs, and/or tapers. Design considerations include heat transfer, mounting technique, parting line, clamping mechanism, mold release,[275] venting, and material stability in storage and during the RM process. The preferred contour for any parting line is the straightest path possible. By this means, mold construction costs can be reduced and demolding will be the easiest means possible.

When two products like a container and its lid are to be molded together, as in blow molding, they may be separated after the molding by employing a removable cutter or annular wedge at the parting line. Another technique is by molding it oversize to provide a resting flange, then cutting it to separate the products.

Draft on the cavity wall such as 1° is recommended to facilitate product removal. Lower-shrinkage plastics like PC and PMMA requires 1½ to 2°. Undercuts are possible, but they should be kept to a minimum. Making provisions for undercuts or no drafts usually requires higher mold costs because the mold will require action such as core pulls or splitting a mold to allow separation parallel to the undercut groove. This type of mold action usually requires additional cycle time thus increasing cost.

As with other mold operation process mold release agents are usually required because the plastic melt can adhere to the surface of the mold cavity. Molds with very little or no draft usually require a release agent. Like other molding operations, a textured cavity can provide a textured product surface. Most texturing of cavities is by chemical etching so it is important to use the appropriate mold material to create a particular texture. An effective release is needed at the parting line to aid in demolding.

There are mold release agents that can be baked or applied to the cavity by wiping. By coating with fluorocarbon, the need for mold release could be eliminated. With conventional RM, after the initial mold-release agent is applied, several hundred products can usually be molded before a strip-down of the mold cavity is required and another baked-on coating is applied. During this time, some touch-up of the mold may be required.

Design

RM molds can be designed to operate manually or automatically open, incorporate vents, and perform for short or long time fabricating runs. Of the usual competing single-sided thermoforming, blow molding, and rotational molding only rotational molding has the potential to yield uniform wall thickness for the most complex product.[1, 2, 4, 6, 32, 176]

When possible it is always best to design the molded product to permit producing a mold that minimizes costly complications in producing the mold. Guide to the design approach follows:

1 maximize as much as possible side wall drafts,

2 change deep pocket areas for better heat flow and thicker walls,

3 maximize tolerances but keep as low as possible to reduce cost of plastic,

4 keep pressure loads at component mounts below 100 psi,

5 keep high stress areas away from parting lines,

6 avoid flat surfaces with straight lines,

7 provide simplified parting lines, and

8 keep inserts away from sidewalls for good material fill.

The Association of Rotational Molders International (ARMI) has published a design manual for rotational molding (ARMI, 435 North Michigan Avenue, Suite 1717, Chicago IL 60611-4067, USA; telephone 312-644-0828). ARM represents the rotomolding industry internationally. It includes molders, plastic, and equipment manufacturers, design organizations, and professional consultants. ARM is also the major information-disseminating organization in the rotational molding industry. It has compiled a comprehensive library with the industry's design manual. Another important organization on this subject is the Rotational Molding Development Center (RMDS) at the University of Akron. It was founded in 1986 to provide for the industry's future research needs.[470, 477]

14 COMPRESSION MOLDING

Introduction

Compression molding (CM) encompasses different techniques in processing plastics. To be reviewed are the basic compression molding process (Figure 14.1), the transfer molding process, resin transfer molding process (Chapter 15), compression-transfer molding process, and other molding processes. These compression molding methods provide different capabilities to fabricate products to meet performance requirements using different materials (Tables 14.1 and 14.2).

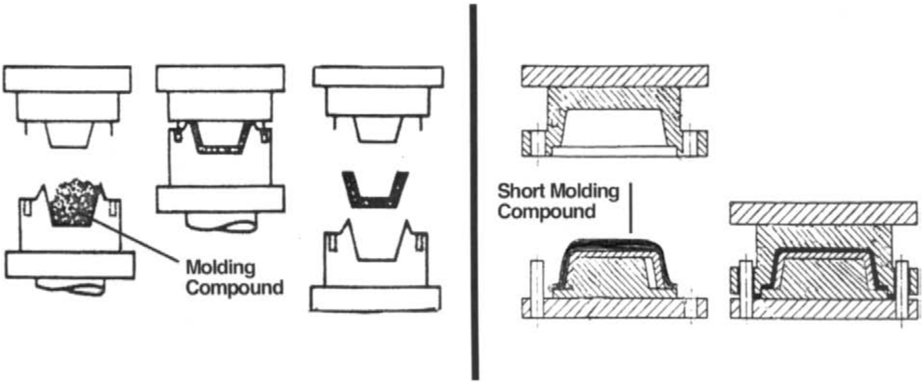


Figure 14.1 Schematics of compression molding plastic materials

Compression molding is an old and common method of molding thermoset (TS). It now processes TS plastics as well as other plastics such as thermoplastics (TP), elastomers (TS and TP), and natural rubbers (TS). By this method, plastic raw materials are converted into finished products by simply compressing them into the desired shapes

Table 14.1 Example of applications for compression molded thermoset plastics

Material	Performance	Application
Phenol-formaldehyde		
General-purpose	Durable, lowcost	Small housings
Electrical grade	High dielectric strength	Circuit breakers
Heat resistant	Low heat distortion	Stove knobs
Impact resistant	Strong	Appliance handles
Urea formaldehyde	Color stable	Kitchen appliances
Melamine formaldehyde	Hard surface	Plastic dinnerware
Alkyd	Arc resistant	Electrical switchgear
Polyester	Arc resistant	Electrical switchgear
Diallyl phthalate	High dielectric strength	Multipin connectors
Epoxy	Soft flowing	Encapsulating electronic components
Silicone	Heat resistant	Encapsulating electronic components

by using molds, heat, and pressure. This process can mold a wide variety of shapes ranging from parts of an ounce to 100 lb or more.[265, 469, 484]

The process requires a press with heated platens or preferably heating in the mold. Basically a two-part mold is used (Figure 4.1) (Chapter 17). The female or cavity part of the mold, when using a molding compound, is usually mounted on the lower platen of the press, while the male or plunger part is aligned to match the female part and is attached to the upper platen (Figure 14.1). If a plastic impregnated material (sheet, mat, etc.) is used the female or cavity part of the mold is usually mounted on the upper platen of the press, while the male or plunger part is aligned to match the female part and is attached to the bottom platen (Figure 14.1).

The plastic molding material is weighed out and is usually preheated before charging (transferring) to the cavity part of the heated mold. After charging the mold, the press is closed bringing the two parts of the mold together. This allows the molding material to melt and flow through filling the cavity between the two parts of the mold, and at the same time pushing out any entrapped air ahead of the melt so as to fill the mold cavity completely. After holding the plastic in the mold for the time specified for a proper cure under the required temperature and pressure, the pressure is released, the mold opened, and the solid molded plastic part discharged. In a modern high-speed automatic compression press all the operations are performed automatically.

The necessary preheating and mold heating temperatures and mold pressure may vary considerably depending upon the thermal and rheological (refers to the deformation and flow properties of the plastic) properties of the plastic (Chapter 1). For a typical compression molding

Table 14.2 Comparing compression molded properties with other processes

Process	Reinforcement wt%	Compressive Strength		Tensile Modulus		Flexural Strength		Tensile Strength		Impact Strength		Heat Distortion at 1.8 MPa		Dielectric Strength	
		MPa	ksi	GPa	10^6 psi	MPa	ksi	MPa	ksi	J/m	ft · lbf/ft	C	F	kV/cm	kV/in.
Spray	30–50 glass-polyester	100–170	15–25	5.5–12	0.8–1.8	110–190	16–28	60–120	9–18	210–640	48–144	175–205	350–400	80–160	200–400
Compression	15–30 glass-SMC	100–210	15–30	11–17	1.6–2.5	120–210	18–30	55–140	8–20	130–1,150	96–264	205–260	400–500	120–180	300–450
Compression	25–50 glass mat-polyester	100–210	15–30	6.2–14	0.9–2.0	70–280	10–40	170–210	25–30	530–1,050	120–240	175–205	350–400	120–240	300–600
Filament winding	30–80 glass-epoxy	310–480	45–70	28–62	4.0–9.0	690–1,850	100–270	550–1,700	80–250	150–3,200	480–720	175–205	350–400	120–160	300–400
Pultrusion	40–80 glass mat-polyester	210–480	30–70	28–41	4.0–6.0	690–1,050	100–150	410–1,050	60–150	400–3,200	540–720	205–260	400–500	80–160	200–400

thermoset material preheat may be at 200F (93C) and mold heat and pressure may be near 250 to 350F (121 to 177C) and 1000 to 2,000 psi (6.9 to 13.8 MPa). A slight excess of material is usually placed in the mold to insure it being completely filled and this excess is squeezed out between the mating surfaces of the mold in a thin, easily removed film known as flash. As shown in Figure 14.2 flash can form in different positions based on how it is to be removed. Different methods are used to remove flash such filing, sanding, and/or tumbling. There are systems where parts are frozen (dry ice) making it easier for certain types of plastic parts to be deflashed.

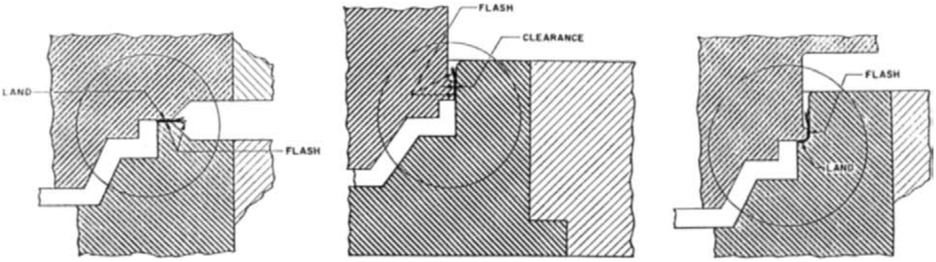


Figure 14.2 Examples of flash in a mold: (a) horizontal, (b) vertical, and (c) modified vertical

In the case of a thermoplastic, the molding temperature cycle is from heating to plasticizing the plastic, to cooling in the mold under pressure, the pressure released, and the molded article removed. When TS is used the mold need not be cooled at the end of the molding operation or cycle, as the plastic will have hardened and can no longer flow or distort (Chapter 1).

The molding cycle takes anywhere from a few minutes to an hour depending upon the type of plastic used and the size of the charge. The cycle steps are

1 charging;
2 closing the press;
3 melting the plastic;
4 applying full pressure and heat;
5 curing for TSs or cooling for TPs;
6 discharging or ejecting the molded part.

Most of the time is consumed in the cure or cooling stage, while some of the other stages could take only a few seconds.

Compression molding was the major method of processing plastics worldwide during the first half of the last century because of the development of phenolic plastics (TSs) in 1909. By the 1940s this situation began to change with the development and use of thermoplastics (TPs) in injection molding (IM).

CM originally processed about 70wt% of all plastics, but by the 1950s its share of total production was below 25%, and now that figure is about 3% of all plastic products produced internationally. Worldwide 350 million lb/yr are estimated to be consumed. This change does not mean that CM is not a viable process; it just does not provide the much lower cost-to-performance benefit of TPs that are injection molded, particularly at high production rates. In the early 1900s plastics were almost entirely TS (95wt%) used in different processes, but that proportion had fallen to about 40% by the mid-1940s and now is about 10%.

TSs has experienced an extremely low total growth rate, whereas TPs have expanded at an unbelievably high rate. Regardless of the present situation, CM is still important, particularly in the production of certain low-cost products as well as heat-resistant and dimensionally precise products. CM is classified as a high pressure process. Some TSs may require higher pressures while others require lower pressures of down to 50 psi (0.35MPa) or even just contact/zero pressure.

The advantages that keeps the compression process system popular are due primarily to the simple operation that defines the system. The heated cavity is filled directly and then pressurized for the duration of the cure cycle. Examples of advantages are as follows:

1 Tooling costs are low because of the simplicity of the usual molds.

2 Little material is wasted since there are usually no sprues or runners [when not compared to runnerless injection molding (Chapter 4)].

3 TSs when compared to TPs are not subject to retaining internal stresses after being cured.

4 Mechanical properties remain high since material receives little mastication in the process and when using reinforcements they are literally not damaged or broken.

5 Less clamping pressure required than in most other processes.

6 Capital equipment is less costly.

7 Wash-action erosion of cavities is minimal and mold maintenance is low since melt flow length is short.

Limitations of the method include:

1 Fine pins, blades, and inserts in the cavity can become damaged as the press closes when cold material is used in the cavities.

2 Complex shapes may not fill out as easily as by the transfer or injection molding processes.

3 Extremely thick and heavy parts will cure more slowly than in transfer or injection molding, but preheating preforms or powder can shorten these cures.

4 Thermosets with their low viscosity will produce flash during their cure that has to be removed.

Mold

Three general types of molds are used for CM. In the positive mold (Figure 14.3a) all the material is trapped in the mold cavity. The pressure applied compresses the material into the smallest possible volume. Any variation in the weight of the charge will result in a variation in part thickness. In multicavity molds, if one cavity has more material than the others, it will receive proportionately greater pressure. Multiple cavities, therefore, can result in density variations between parts if loading is not done with some degree of precision control.[1, 278–284]

A flash mold (Figure 14.3b) has a narrow land or pinchoff area around the cavity. Material is compressed in the cavity to a density that will match the force applied. Excess material escapes across the pinchoff line as flash. Immediately beyond the pinchoff line, the surface is relieved to allow the flash to fluff out rather than to cure in a hard skin that would adhere tightly to the metal surface.

The semipositive mold (Figure 14.3c) is by far the most popular. It combines the best features of the positive and the flash molds. Since its design includes a plastic material well of larger diameter, with a tight fitting force above the cavity, the material is trapped fairly positively and the plastic is forced to flow into all corners of the cavity. As the material picks up more heat and becomes fluid, it escapes between the force and cavity sidewalls as flash, allowing the force to seat on the land area.

Clearance between the sidewall of the cavity and the OD of the force generally is about 0.004 in. Variation in this clearance will vary the density of the molded part. The gases that are released from curing certain TS plastics, as well as the air in the cavity, must be allowed to

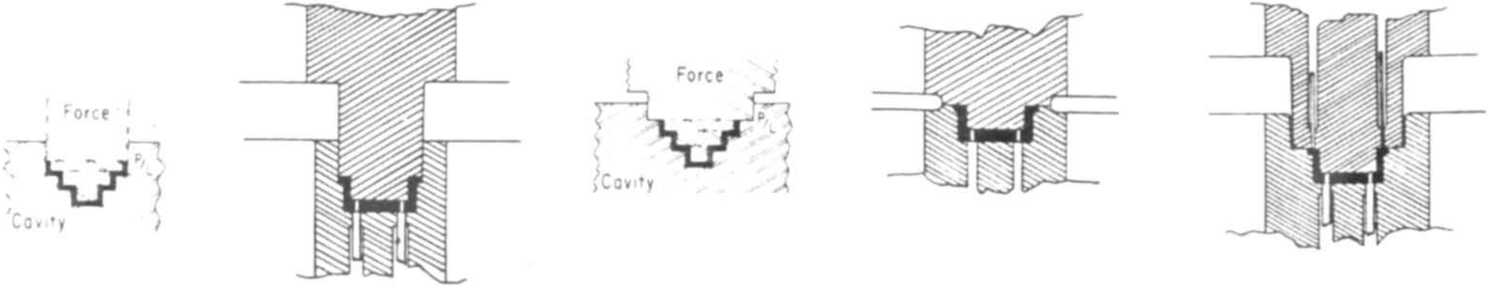

Force
P/L
Cavity
Force
P/L
Cavity

Figure 14.3 Example of mold types: (a) positive compression mold, (b) flash compression mold, and (c) semipositive compression mold

escape. They will, in some cases, filter through the flash and/or the clearance around the ejector pins. Usually vents are also included in the mold to permit release of these gases. When processing TPs there should not be a problem in flash occurring. However air in the cavity has to be released so vents in the mold are used that is a take off of injection molding molds.[3]

The TS gases are more of a problem with urea and melamine than with phenolic. To ensure they do not become entrapped in the molding material during compression molding, and in turn weaken the molded part or cause surface blemishes, it often is advisable to open the mold to allow gases to escape. This is called breathing or bumping. It amounts to sufficient reduction in clamp pressure to allow the pressurized gases to blow their way out, and/or sufficient opening movement to create a slight gap for trapped gases to escape effortlessly.

To aid in controlling the thickness of molded parts and/or support the pressure loads put on sections of a mold, lands in the mold are used. Examples of lands are shown in Figure 14.2. Figure 14.4 shows the land locations used in a mold that supports the split-wedge in the mold.

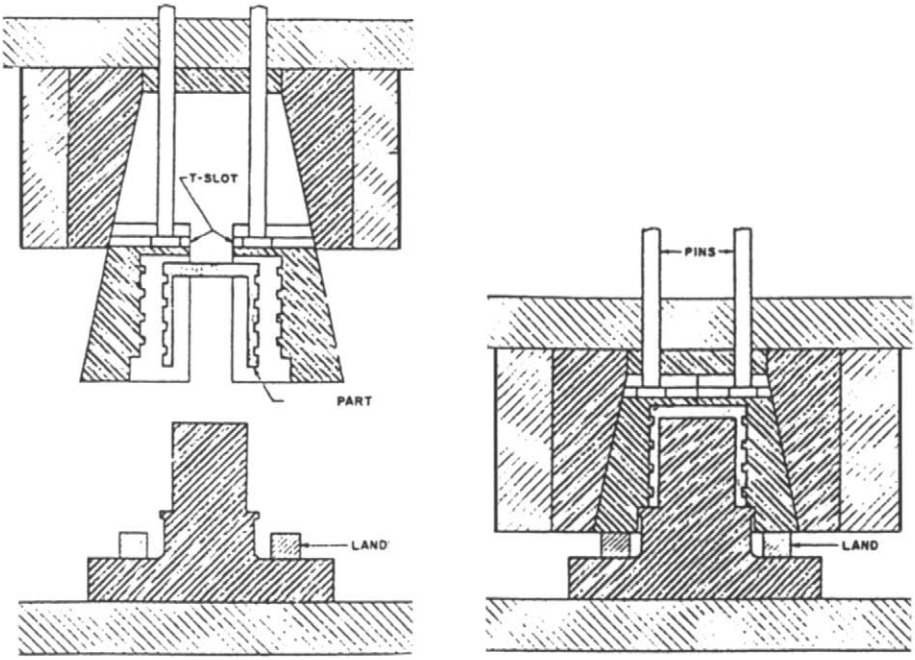


Figure 14.4 Example of land locations in a split-wedge mold

When plastics, particularly compounds, prepregs, and sheet materials that are filled with reinforcements such as glass fibers, the matting edges of the mold cavity require special treatment (Chapter 17). The target is to ensure proper and clean-cut edges of the parts. The materials of construction can overlap the edges prior to or during molding.[3]

Machine

The CM machines are usually referred to as compression presses. They are primarily hydraulic or, in limited use, pneumatic. Either of these systems can have the usual straight lockup system or toggle lockup system (Chapter 4). These presses may be either down-acting or up-acting. The down-acting type is used for the fully automatic compression presses so that the lower mold half is at a fixed height to align with the material feeder and molded product stripper tables.

Different actions in molds occur such as using ejector pins to remove molded parts from their cavities. Side actions of molds may be required to remove parts that have undercuts. Other actions may be required such as unscrewing threaded parts, including inserts, and so on (Chapter 17).

The presses are available in all sizes to meet the many different requirements for parts to be molded. These differences include short to long curing cycle times, small to large parts requiring different pressures (clamp tonnages), and so on. They range from less than a ½ to thousands of tons with platens 4 by 4 in. to at least 10 by 20 ft. The usual press has two platens and others have up to at least 30 platens that can simultaneously mold flat sheets or other products. There are presses with shuttle molds and those that have a series of individual presses (3 to at least 25) that rotate providing the TS plastic to complete its curing cycle, permit ease of including inserts, etc. Presses usually have their platens parallel to each other and there are those that open like clam shells referred to as book type. Other processes reviewed in this book provide examples of these type presses to fabricate by their respective methods (Chapters 4, 12, 15, and 16).

In use are stamping compression molding presses. Plastic used can be TS sheet molding compounds (SMCs) and stampable reinforced thermoplastic sheet (STX) material (STX is a registered tradename; Azdel Inc., Shelby, NC). It is usually composed of a glass fiber-thermoplastic RTP (Chapter 15).

Plastic

Different TS plastics are used such as phenolics, TS polyesters, DAPs, epoxies, ureas, melamines, and silicones, all with their own processing requirements and performance molded properties based on their compositions. [Note there are TS and TP polyesters (Chapter 2)]. Also used are TPs. TSs are used primarily in CM and TPs in injection molding, extrusion, blow molding, etc. In this review the emphasis is on TSs, which have different processing characteristics to TPs (Chapter 1).

Materials can be unreinforced or reinforced/filler compounds, sheet molding compounds (SMC), bulk molding compounds (BMC), prepregs, preforms or mats with liquid resins, etc. With TSs, they cure via A-B-C stages that identify their heat cure cycle. A-stage is uncured (in the form received from a material supplier), B-stage is partially cured with heat, and C-stage is fully cured. A typical B-stage is TS molding compounds and prepregs, which in turn are processed to produce C-stage fully cured plastic material products in compression molds. TSs when heated go through crosslinking chemical reactions to produce hard or rigid plastic product. TPs during molding go through a melting stage when heated followed with a hardening stage when cooled (Chapter 1).

An example of very popular CM materials are bulk molding compounds (BMCs); in Europe they are called dough molding compounds (DMCs). They are formulated from different percentages of TS polyesters filled with glass fibers of lengths up to ½ in (13 mm) and fillers. The BMCs flow easily and provide high strength (Chapter 15). Also popular as CM molding materials are the TS vinyls used for phonograph records, etc. TP vinyls are crosslinked to turn them into TS vinyls (Chapter 1).

Very soft flowing TSs are required for molding around very delicate inserts. Large quantities of electronic components such as resistors, capacitors, diodes, transistors, integrated circuits, etc. are encapsulated with such soft-flowing TS compounds. Principally used are epoxies by compression molding (and transfer molding). Silicone molding compounds are used occasionally where higher environmental temperatures are required of the encapsulated part that can be exposed up to 500F (260C) or more. TS polyester compounds, that are less expensive than epoxies, or silicones that are more expensive, are also selected when their requirements suffice (Chapter 2).

In the use of preform and mat-reinforced molding, the plastic may be added either before or after the reinforcement is positioned in the cavity. The preform can be a spray-up of chopped glass fibers deposited on a shaped screen with a minimum of plastic binder (about 1 to 5wt% of resin compatible with the molding resin). Different techniques are used to provide desirable surfaces (Chapter 15).

Depending on the type of material used, and the size and thickness of the product, different temperatures, pressure, and time schedules are used. Temperatures range from about 200 to 350F (93 to 177C). Pressurewise, the range is from about 1,000 to 2,000 psi (6.9 to 13.8 MPa). Time cycles can range from less than 1 minute to many minutes. The process called matched-die molding, generally identifies CM operating at the lower pressures.

Polytetrafluoroethylene

Processing the usual thermoplastics (PE, PP, PVC, PS, etc.) sets up no special technique. However certain TPs such as polytetrafluoroethylenes (PTFEs) require special techniques because they do not have the usual easy melt flow. CM is used to fabricate cylindrical billet, molding, or sheet shapes of PTFE. This type of CM is also called isostatic compression molding. As an example electric-grade tapes are skived from billets with a wall thickness of 75 to 100 mm. The granular plastic goes through the three stages of preforming, sintering (heating) and cooling.

The large quantity of plastic and the length of time needed to produce a shape requires careful attention to factors that affect fabrication such as the handling and storage of the plastic. High temperature storage of granular PTFE can lead to compaction during handling. Plastic should be conditioned at temperatures of 21 to 25C (70 to 77F) before molding to reduce clumping and ease handling. Dew point conditions should be avoided to prevent moisture from condensing on the cold powder that will expand during sintering and crack the molding. Molding below 20C (68F) should be avoided because PTFE will undergo a 1% volumetric change at a transition temperature of 19C (66F).

Preforms molded below 20C can crack during sintering. Sintering is the process of holding the fusible pressed powder part (PTFE, nylon, etc.) at a temperature just below its melting point for a specific time period. Powdered particles are fused (sintered) together but the mass as a whole does not melt. PTFE is an excellent thermal insulator that is about 2,000 times less than copper. The most common way of delivering heat to the preform is by circulation of hot air. A large volume of air has to be recirculated because of its low thermal capacity.

After being removed from the mold it is heated to a higher temperature to completely fuse the sintered material resulting in property increases (tensile strength, etc.), ductility, and usually density. Good temperature control is critical to achieving uniform and reproducible part dimensions and properties. Sintering of the preform takes place in an oven where massive volumes of heated air are circulated. Initial heating of the preform leads to thermal expansion of the part. After PTFE melts, relaxation of the residual stresses occur where additional recovery takes place and the part expands. The remaining air begins to diffuse out of the preform after heating starts. The adjacent molten particles begin to coalesce slowly; usually hours are required because of the massive size of PTFE molecules. Fusion of the particles is followed by elimination of the voids, where almost no air is left.

Cooling at a controlled rate after sintering takes place ensures proper crystallization and annealing of the plastic. Properties of PTFE (similar to other semicrystalline polymers) are controlled by the crystalline phase content of the part (Chapter 1). To remove residual stresses in the plastic, annealing is used, which takes place after a period of time. The final crystallinity of the part depends on the annealing temperature. A part which is annealed below the crystallization temperature range [<300C (<572F)] will only undergo stress relief. Annealing at a temperature in the crystallization range [300 to 325C (572 to 612F)] results in higher crystallinity. The result is higher specific gravity and opacity in addition to stress relief.

Processing

Processing conditions such as temperature, pressure, and molding cycle differ for the different plastics. There exists a wide range of flow characteristics with the different plastics and also within a specific plastic when they have different compositions. These molding compounds are mixtures of constituents, usually of different size and shape. The compounds themselves present the greatest number of variables that must be understood and properly applied. The processing conditions with TSs as well as TPs ultimately effect mechanical, chemical, electrical, aesthetic, and other properties.

Many TS compounds are heated to about 300 to 400F (149 to 204C) for optimum cure; but can operate as high as 1200F (650C). Over heating any materials could degrade their performance or could cause them to solidify rapidly before the mold cavity is completely filled.

Preheating is often used to reduce the molding cycle. It can aid in providing even heat through the material and can cause a more rapid rise in heat than occurs in the mold cavity. A warm surface plate, infrared lamps, hot-air oven, or screw/barrel preheater can accomplish preheating. The best and quickest method is high-frequency (dielectric) heating.

Preheating is usually carried out at 150 to 300F (66 to 149C) followed by quick transfer to a mold cavity. The actual heat depends on the material, the heater capability, and the speed of transfer. Circular preforms are normally used with dielectric heaters so they can be rotated to obtain uniform heating. Pills of compressed compound are used to produce preforms to facilitate handling, reduce the bulk factor in the cavity, and control the uniformity of charges for mold loading. Preforms can also be the shape of the mold cavity.

Compared to other processes, particularly injection molding (IM) for shaping plastics, CM is fairly labor-intensive even if it is automated. However it requires lower capital investment. Molding cycles for CM are generally longer than for IM. If the material used is preheated or preplasticized before it is placed in a mold cavity, molding cycles may be comparable to IM. When CM flash formation in the molds occur, their viscosity during the melting action resembles that of water. Techniques can be used to significantly reduce flash by modifying the mold design.

To aid in reducing cycle time there are molded parts that can finish their cycle in a fixture. After a molded product is removed from the cavity it is still hot and the material is not fully rigid. Any internal stresses in the material may therefore cause the shape of the product to change while it is cooling. Where close tolerances are required and especially where products have thin sections, dimensional accuracy can be met by placing the hot, molded product on a fixture near the press that will hold it until it has cooled.

To improve properties such as mechanical, thermal, and dimensions of certain molded TSs, also certain TPs, they are exposed to a postcure. The part is literally baked in an oven. Experience or a material supplier's recommended times and temperature profiles required to enhance properties are used. Baking also improves creep resistance and reduction in stresses. This postcuring is also used with certain TPs after IM or extrusion to improve their performance.

Postcuring heat is usually below the actual molding heat. It is usually performed in a multistage heat cycle. The reinforcement system of the compound will dictate heating cycles. Products molded from compounds using organic reinforcements are postcured at lower heats than those using glass and mineral reinforcements. Products of uneven thickness will exhibit uneven shrinkage. This shrinkage effect is included in the mold design.

Heater

There are many heat choices available and a wide choice of temperature controls as there is with other fabricating processes. They range from simple mechanical thermostats to solid state units with PID control, to microprocessors that are proportional, programmable, and self-tuning (Chapter 3).

Electrical heating, through the use of heater coils, strips, or cartridges, is the most popular method. Higher temperatures for faster cycles are easily obtained. Recognize that electric mold heating is only as fast as the wattage put into it. It is a cleaner system than steam that was used many decades ago.

Steam heat provided the fastest recovery time of any system because of the oversize source available in the boiler room. It offered a uniform mold temperature, as do all liquid systems, but is limited to about 350F (177C) maximum. Steam heat is also messy and requires good maintenance, or rusty pipes and leaks become all too common. Steam controls and the accompanying valves are expensive and many are not dependable.

Hot oil heat offers the benefits of higher temperatures from a liquid system. It results in probably the most uniform mold temperatures primarily because the fluid is being constantly circulated. Recovery time, however, is limited to the total heat capacity designed into the circulating unit.

High pressure water systems are also available that heat by continuously circulating hot water. The advantage is less corrosion than steam since the oxygen is not replenished in the closed circuit. Also, temperatures are more uniform than steam because, like hot oil, it is a dynamic system. These systems are expensive and costly to maintain.

Gas flames have been used on rotary presses. Gas also has been used with some exotic materials requiring very high temperatures [over 2000F (1,093C)].

Automation

A variety of feeders have been designed to move the molding material into the mold, and special strippers built to remove the molded parts. All of these have the common goal of faster, more efficient, and automatic production. The feeders include feeding cold powder through tubes from overhead hoppers, reciprocating, feed boards, etc., and the feeding of preheated, partially or fully plasticated material from infrared heated hoppers, RF heating units, or screw plasticators.

Automatic strippers have included many combinations of air blow-off, metal combs, and catch trays or chutes. Programmable robots are used for this type of work. These sophisticated units are also used to add inserts before loading the mold.

Recently all of the temperature, pressure, and time controls have been replaced with a single microprocessor-based controller. A number of these are available and they allow for complex pressure and temperature curves to be programmed with multiple soaking levels and variables that can be chosen. Built-in memories recall previous programs and cassettes can store them on the shelf. Interfaces can connect with a central host computer for data collection or actual machine setup and supervision. The result is more flexible, more exacting, and easier to control modern molding equipment (Chapter 3).

Transfer Molding

Shaw of Pennsylvania developed this plastic transfer molding process during the 1930s. It is a method of compression molding, principally thermoset plastics. Heat and pressure in a transfer chamber (pot) first soften plastic. After the heating cycle it is forced by a ram at high pressure through suitable sprues, runners, and/or gates into a closed mold to produce the molded part or parts using one or normally two or more cavities (Figure 14.5). Usually dielectrically preheated circular preforms are fed into the pot. Plastic remaining in the transfer chamber after mold filling is called a cull. Unless there is slight excess in this chamber, one cannot be sure that the cavity(s) was completely full.

Since the plastic entering the cavities is melted it requires less force to fill the cavities than compression molding With conventional CM there is more force in the cavities as the solid plastic is melted. The result is that more intricate parts can be molded as well as encasing intricate devices such as electronic.

Compression-Injection Molding

Usually called injection-compression molding (ICM). Details are in Chapter 4. The essential difference when compared to IM lies in the manner in which the thermal contraction in the mold cavity that occurs during cooling (shrinkage) is compensated. With conventional injection

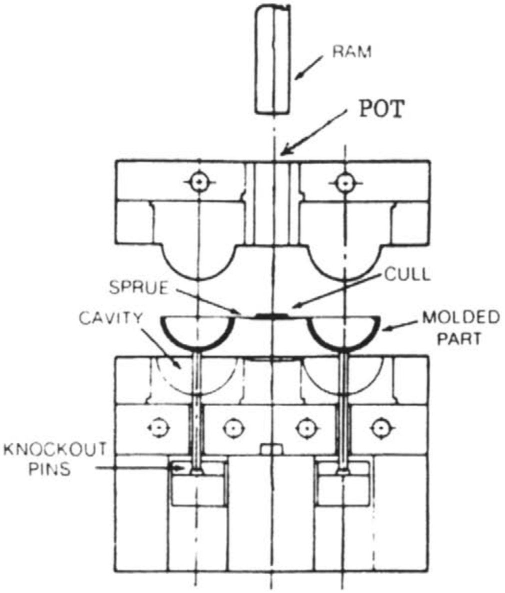


Figure 14.5 Schematic of transfer molding

molding, the reduction in material volume in the cavity due to thermal contraction is compensated basically by forcing in more melt during the pressure-holding phase. By contrast with CIM, a compression mold design is used where a male plug fits into a female cavity rather than the usual flat surface parting line mold halves for IM

Hydrostatic Compression Molding

Hydrostatic molding is a suitable alternative to compression molding techniques for the production of plastics that do not have the usual melt flow behavior, such as previously reviewed in the Plastic section for polytetrafluoroethylene.

15 REINFORCED PLASTIC

Overview

Industry continues to go through a major evolution in reinforced plastic (RP) structural and semi-structural materials. RP has been developed to produce an exceptionally strong and corrosive material. The RP products normally contain from 10 to 40wt% of plastic, although in some cases plastic content may go as high as 60% or more (Figures 15.1 and 15.2).

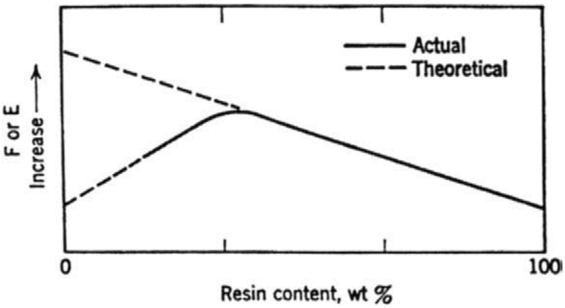


Figure 15.1 Effect of matrix content on strength (F) or elastic moduli (E) of reinforced plastics

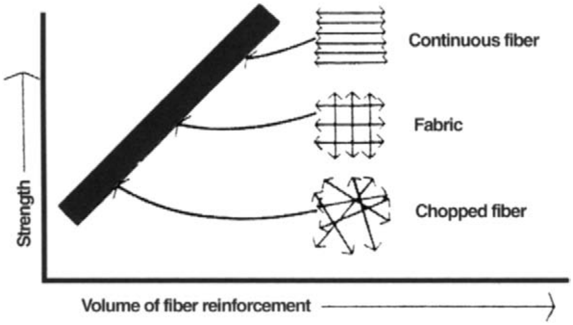

Continuous fiber
Fabric
Chopped fiber
Strength
Volume of fiber reinforcement

Figure 15.2 Properties vs. amount of reinforcement

RPs, also called plastic composites or composites, are tailor-made materials which provide the designer, fabricator, equipment manufacturer, and consumer, engineered flexibility to meet different properties, environments, and create different shapes. They can sweep away the designer's frequent crippling necessity to restrict performance requirements of designs to traditional monolithic materials. The objective of a plastic composite is to combine similar or dissimilar materials in order to develop specific properties related to desired characteristics. Composites can be designed to provide practically any variety of characteristics. For this reason, practically all industries use them. Economical, efficient, and sophisticated parts are made, ranging from toys to bridges to reentry insulation shields to miniature printed circuits to missiles.

Almost any thermoset or thermoplastic matrix (resin/plastic) property can be improved or changed to meet varying requirements by using reinforcements. Typical resins used include polyester (thermosets and thermoplastics), phenolic, epoxy, silicone, diallyl phthalate, alkyd, melamine, polyamide, fluorocarbon, polycarbonate, acrylic, acetal, polypropylene, ABS copolymer, and polyethylene (Chapter 2). Reinforced thermosets (RTSs) predominate for the high performance applications. However there has been successful concentrated effort to expand use of reinforced thermoplastics (RTPs) in the electronic, automotive, aircraft, underground pipe,[1] appliance, camera, and other high performance products.[49, 285–288, 439] Result is that over 50wt% of all RPs are thermoplastic types, principally injection molded, using short and long glass fibers (Chapter 4).

Fiber strengths have risen to the degree that 2-D and 3-D RPs can be used producing very high strength and stiff RP products having long service lives. Products in service have over a half-century of indoor and outdoor service. RPs can be classified according to their behavior or performance which varies widely and depends on time, temperature, environment, and cost. The environment involves all kinds of conditions such as amount and type of load, weather conditions, chemical resistance, and many more. Directly influencing behaviors or performances of RPs involve type of plastic, type of reinforcement, and process used. These parameters are also influenced by how the product is designed. Figure 15.3 and Tables 15.1 to 15.3 provide information on properties, processes, and characteristics of RPs.

Definition

A precise definition of reinforced plastics can be difficult (or impossible) to formulate because of the scale factor. At the atomic level all elements

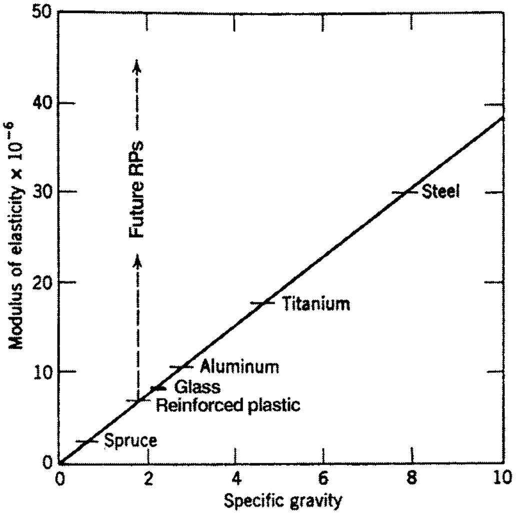


Figure 15.3 Modulus of different materials can be related to their specific gravities with RPs providing an interesting graph

Table 15.1 Review of a few processes to fabricate RP products

- Compression Molding
  - Flexible Plunger
  - Flexible Bag Molding
  - Laminate
- Hand Lay-Up
  - Vacuum Bag Molding
  - Vacuum Bag Molding and Pressure
  - Pressure Bag Molding
  - Autoclave Molding
  - Autoclave Press Clave
  - Wet Lay-Up
  - Bag Molding Hinterspritzen
  - Contact Molding
- Filament Winding
  - Fabricating RP Tank
- Injection Molding
- Marco Process
- Pultrusion
- Reactive Liquid Molding
- Reinforced Resin Transfer Molding
- Reinforced Rotational Molding
  - Squeeze Molding
- SCRIMP Process
- Soluble Core Molding
  - Lost-Wax Process
- Spray-Up
- Stamping
  - Cold Forming
  - Comoform Cold Molding

Table 15.2 Examples of reinforced thermoplastic properties

Plastic	Glass Fiber Content, (wt %)	Specific Gravity, D 792	Tensile Strength (MPa), D 638	Tensile Elongation (%), D 638	Tensile Modulus (GPa), D 638	Flexural Strength (MPa), D 790	Flexural Modulus (GPa), D 790	Compressive Strength (MPa), D 695	Impact Strength, Izod Notched, (J/m), D 256
ABS	10	1.10	65	3.0	4.6	102	4.5	83	64
	20	1.22	76	2.0	5.1	107	4.9	97	59
	30	1.28	90	1.4	6.3	116	6.4	104	53
Acetal	10	1.54	72	2.4	6.6	107	6.1	69	53
	30	1.63	83	2.0	7.7	114	7.2	81	43
Nylon 6	15	1.25	104	4.0	5.9	159	5.4	97	80
	30	1.37	166	3.0	7.2	200	6.9	166	117
Nylon 6/6	13	1.23	97	4.0	6.2	173	4.5	93	53
	30	1.37	173	3.0	9.0	235	9.0	186	107
Nylon 6/12	30	1.30	135	4.0	8.3	193	7.6	138	117
Polycarbonate	10	1.26	83	9.0	5.2	110	4.1	97	107
	30	1.43	121	2.0	8.6	141	6.9	117	128
Polyester, TP	30	1.52	131	4.0	8.3	193	7.9	124	96
Polyethylene	10	1.04	36	4.0	2.5	46	2.5	35	75
	30	1.18	59	3.0	5.0	89	4.9	41	91
Polyphenylene sulfide	40	1.64	152	3.0	14.1	255	13.0	145	80
Polypropylene	10	0.98	43	4.0	2.5	54	2.4	41	43
	20	1.04	45	3.0	3.7	57	3.6	45	59
	30	1.12	47	2.0	4.4	63	4.3	47	69
Polypropylene	10	0.98	50–59	4.0	3.7	72–94	3.5	43–44	64–75
Polystyrene									
High heat copolymer	20	1.22	90	1.2	8.3	131	7.9	110	59
High heat terpolymer	30	1.35	83	1.8	6.5	123	5.7	76	80
Polysulfone	20	1.38	97	2.5	6.0	138	5.9	124	64
	40	1.55	124	1.5	11.6	173	10.7	138	80
Polyurethane	10	1.22	33	48.0	0.7	43	0.6	35	747
PVC	20	1.58	97	3.0	0.8	145	6.9	83	80
SAN	20	1.22	100	1.8	8.6	131	7.6	121	64
	35	1.35	110	1.4	10.4	155	9.3	45	53

Table 15.3 Examples of properties and processes of reinforced thermoset plastics

Thermoset	Property	Process
Polyesters	Simplest, most versatile, economical, and most widely used family of resins; good electrical properties, good chemical resistance, especially to acids	Compression molding, filament winding, hand lay-up, mat molding, pressure bag molding, continuous pultrusion, injection molding, spray-up, centrifugal casting, cold molding, encapsulation, etc.
Epoxies	Excellent mechanical and adhesion properties dimensional stability, chemical resistance (especially to alkalis), low water absorption, self-extinguishing (when halogenated), low shrinkage, good abrasion resistance	Compression molding, filament winding, hand lay-up, continuous pultrusion, encapsulation, centrifugal casting
Phenolics	Good acid resistance, good electrical properties (except arc resistance), high heat resistance	Compression molding, continuous lamination, high pressure process
Silicones	Highest heat resistance, low water absorption, excellent dielectric properties, high arc resistance	Compression molding, injection molding, encapsulation
Melamines	Good heat resistance, high impact strength	Compression molding
Diallylgphthalates	Good electrical insulation, low water absorption	Compression molding

are composites of nuclei and electrons. At the crystalline and molecular level materials are composites of different atoms. And at successively larger scales materials may become new types of composites, or they may appear to be homogeneous (Chapter 1).

Wood is a complex composite of cellulose and lignin; most sedimentary rocks are composites of particles bonded together by natural cement; and many metallic alloys are composites of several quite different constituents. On a macro scale these are all homogeneous materials.

In this review, RPs are considered to be combinations of materials differing in composition or form on a macro scale. But all of the constituents in the plastic composite retain their identities and do not dissolve or otherwise completely merge into each other. This definition is not entirely precise. It includes some materials often not considered to be composites. Furthermore, some combinations may be thought of as composite structures rather than composite materials. The dividing line is not sharp and differences of opinion do exist. Regardless the name composite literally identifies thousands of different combinations with very few that include the use of plastics. In using the term composites when plastics are involved the more appropriate term is plastic composites or just RP.

Many combinations of reinforcements and plastics are used by industry to effect a diversity of performance and cost characteristics. These may be in layered form, as in typical melamine-phenolic impregnated paper sheets, and polyester impregnated glass fiber mat or fabric, or in molding compound form, as in glass or cotton-filled polyester, phenolic, or urea molding compounds. Inline compounding and injection molding thermoplastics with long glass fibers can be performed. Glass fibers (rovings, etc.) can be fed into a single- or twin-screw extruder where the TP is melted. It cuts the reinforcement and provides an excellent mix. All these resulting composites have many properties superior to the component materials.[4, 22, 173, 210]

Basically a plastic composite is the assembly of two or more materials made to behave as a single product. Examples include vinyl-coated fabric used in air mattresses or laminated metal bonded together with a plastic adhesive used in helicopter blades. The RP type of composite combines a plastic with a reinforcing agent that can be fibrous, powdered, spherical, crystalline, or whisker, made of organic, inorganic, metallic, or ceramic material. To be structurally effective, there must be a strong adhesive bond between the resin and reinforcement.

Fibrous Composite

The large-production reinforcing agent used today is primarily glass. Other fibers include cotton, cellulosic fiber, sisal, polyamide, jute, carbon, graphite, boron, whiskers, steel, and other synthetic fibers.[10, 12, 289-291, 466] They all offer wide variations in composition, properties, fiber orientation/construction, weight, and cost (Tables 15.4 and 15.5

Table 15.4 Properties of fiber reinforcements

Type of fiber reinforcement	Specific gravity	Density lb./in.^{3} (g/cm^3)	Tensile strength 10^3 psi (GPa)	Specific strength 10^6 in.	Tensile elastic modulus 10^6 psi (GPa)	Specific elastic modulus 10^8 in.
Glass						
E Monofilament	2.54	0.092 (2.5)	500 (3.45)	5.43	10.5 (72.4)	1.14
S Monofilament	2.48	0.090 (2.5)	665 (4.58)	7.39	12.4 (85.5)	1.38
Boron (tungsten substrate)						
4 mil or 5.6 mil	2.63	0.095 (2.6)	450 (3.10)	4.74	58 (400)	6.11
Graphite						
High strength	1.80	0.065 (1.8)	400 (2.76)	6.15	38 (262)	5.85
High modulus	1.94	0.070 (1.9)	300 (2.07)	4.29	55* (380)	7.86
Intermediate	1.74	0.063 (1.7)	360 (2.48)	5.71	27 (190)	4.29
Organic						
Aramid	1.44	0.052 (1.4)	400 (2.76)	7.69	18 (124)	3.46

and Figure 15.4). With the performance to weight advantages of carbon fiber the 200 to 250 passenger Boeing 7E7 high speed jet (mach 0.85) light weight commercial airplane will have the majority of its primary structure (wings, fuselage, etc.) made of carbon reinforced composites.[465]

Table 15.5 Examples of different carbon fibers

Fiber types	Young's modulus range, 10^6 p.s.i.	Tensile strength range, 10^3 p.s.i.	Raw material employed
Low modulus	5-10	50-150	Rayon, pitch
Intermediate modulus	30-40	450-800	PAN
High modulus	50-60	300-400	PAN, pitch
Very high modulus	70-100	250-350	PAN, pitch

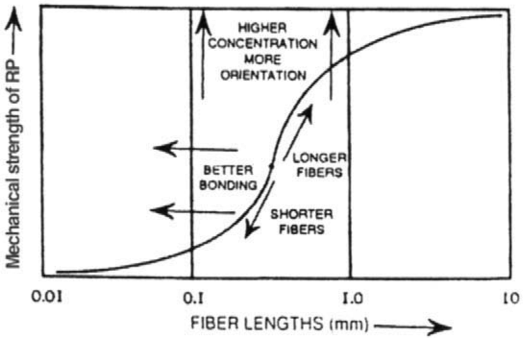


Figure 15.4 Short to long fibers influence properties of RPs

Glass fibers, the most widely used at over 90wt% of all reinforcements, are used in many forms for producing different commercial and industrial products, also for parts in space, aircraft, surface water and underwater vehicles. The older and still popular form is E-glass. S-glass produces higher strength properties (Table 15.4). Other forms of glass fiber exist that meet different requirements. E-CR glass fibers are boron-free E-glass; combines electrical and mechanical properties of E-glass with corrosion resistance.[440]

Materials in the form of fibers are often vastly stronger than the same materials in bulk form. Glass fibers, for examples may develop tensile strengths of 7 MPa (1,000,000 psi) or more under laboratory conditions, and commercial fibers attain strengths of 2,800 to 4.8 MPa (400,000 to 700,000 psi), whereas massive glass breaks at stresses of about 7 MPa (1000 psi). The same is true of many other materials whether organic, metallic, or ceramic.

Acceptance and use of nonwoven fabrics as reinforcement of structural plastics continues to increase. Only with nonwoven fiber sheet structures can the full potential of fiber strength be realized.[427] Great advances have been made developing new fibers and resins, in new chemical finishes given to the fibers, in methods of bonding the fiber to the resin, and in mechanical processing methods. Nonwoven fabrics are inherently better able to take advantage of these developments than are woven sheets.

Strength of commercial reinforced plastics is far below any theoretical strength. Ordinary glass fibers are three times stronger and stiffer for their weight than steel. Nonwoven glass fiber structures usually have strength about 40 to 50% below that of woven fabric lay-ups. But in special constructions, properly treated fibers have produced laminates as strong as the woven product, better in some cases.

Reinforced plastics are usually applied as laminates of several layers. Many variables are important in determining the performance of the finished product. Some of the important ones are: orientation of plies of the laminate, type of resin, fiber-resin ratio, type or types of fibers, and orientation of fibers.

Nonwoven fabrics are fibrous sheets made without spinning, weaving, or knitting. They include felts, bonded fabrics, and papers. The interlocking of fibers is achieved by a combination of mechanical work, chemical action, moisture, and heat by either textile or paper making processes.

Still stronger and stiffer forms of fibrous materials are the unidirectional crystals called whiskers.[1] Under favorable conditions crystal-forming materials will crystallize as extremely fine filamentous single crystals a few microns in diameter and virtually free of the imperfections found in ordinary crystals. Whiskers are far stronger and stiffer than the same material in bulk form.

Fine filaments or fibers by themselves have limited engineering use. They need support to hold them in place in a structure or device. This is accomplished by embedding the fibers in a continuous supporting matrix sufficiently rigid to hold its shape, to prevent buckling and collapse of the fibers, and to transmit stress from fiber to fiber. The matrix may be, and usually is, considerably weaker, of lower elastic modulus, and of lower density than the fibers. By itself it would not withstand high stresses. When fibers and matrix are combined into a composite, a combination of high strength, rigidity, and toughness frequently emerges that far exceed these properties in the individual constituents.

Polyamide (nylon) reinforcements can be in fabric form to provide excellent electrical grade laminates for conventional industrial use. Type used has low water absorption, good abrasion resistance, and resistance to many chemicals.

Carbon and graphite fibers are made by the pyrolysis of certain naturally occurring and man-made fibers, such as regenerated cellulose (rayon) fibers. A wide range of physical, mechanical and chemical properties may be obtained dependent on amount of dehydration. This product is one of the most structurally efficient reinforcements. Unlike any other reinforcement, it retains its 2,800 MPa (400,000 psi) tensile strength when tested up to a temperature of 2700 C (4800F).

Boron in high modulus and strength properties is available with this type of fiber. A vapor deposition process is the principal method to produce boron filaments, using ½ mil tungsten wire as a plating substrate.

Aspect Ratio
The ratio of length to diameter (L/D) or length to thickness (L/T) or major to minor axis of a fiber or other material is the aspect ratio. These ratios have a direct influence and can be used in determining the performance of RPs. High values of 5 to 10 provide for high strength. Theoretically, with proper lay-up the highest performance plastics could be obtained when compared to other materials.[427]

Laminar Composite

Combining layers of materials into a laminated composite is an ancient art, as illustrated by Egyptian plywood, Damascus and Samurai swords, and medieval armor. There are many reasons for laminating; among them are superior strength, often combined with minimum weight; toughness; resistance to wear or corrosion; decoration; safety and protection; thermal or acoustical isolation; color and light transmission; shapes and sizes not otherwise available; controlled distortion; and many others.

Many processes involving temperature fluctuations are made self-regulating by employing laminates of two metals having different coefficients of expansion. When a strip of such metal changes temperature, the different expansivities of the two metals cause the strip to bend, rotate, or elongate, depending upon its shape. In so doing it can make or break electrical contacts, control the position of a damper, or perform many other functions. These bimetals or thermostat metals are servomechanisms; they respond to stimuli from the environment to provide self-regulating behavior. They have this ability because they are composites; each metal by itself would not provide this behavior.

High-strength aluminum alloys are frequently deficient in resistance to corrosion. High-purity aluminum and certain aluminum alloys are considerably more resistant to corrosion but are deficient in strength. By applying surface layers of the corrosion-resistant metal to a core of the strong alloy a clad aluminum composite is achieved that has a corrosion unattainable by either constituent acting alone.

Window glass by itself (in a car, airplane, home, etc.) is hard and durable but brittle, and upon impact may shatter into lethal shards. Polyvinyl butyral (PVB) by itself is a tough but limp and easily scratched plastic material unsuitable for windows. When it is laminated between two sheets of glass a composite results in which the tough plastic layer (PVB), firmly bonded to the glass, prevents the shards from flying when the sheet is struck. Safety glass is thus a composite laminate having properties unattainable by the constituents alone while offering the most valuable characteristics of each. This product has been produced since the early 1930s. Presently development exists in replacing safety glass in automobiles with PC.

Some laminates have become so familiar as to be practically household words. Among them are the plastic composites consisting of layers of heavy strong Kraft paper impregnated with phenolic resins. The resulting sheet is serviceable for many mechanical and electrical purposes. When combined with a melamine formaldehyde saturated decorative overlay sheet, a familiar decorative sheet is obtained that is widely used for counters, furniture, and wall covering. Paper of three types are in common use: Kraft paper (high strength when compared to other papers), alpha paper (electrical use), and rag paper (low moisture pickup with good machinability).

For heavy-duty purposes such as bearings, tough strong fabrics like cotton duck are substituted for the paper. Fabric-based laminates may be further modified with graphite, fluorocarbons, or other low friction materials to provide low-friction composite bearings requiring no lubricant.

Particulate Composite

Particulate composites are used in greater volume than any others because concrete is a particular composite. In many ways, concrete is the archetype of this class of composites. It consists of particles or aggregates of various sizes almost always of mineral materials, bonded together by a matrix of an inorganic cement originally mixed with and hardened by its chemical reaction to water. Many types of particles are employed, at least five different types of Portland cements and several other types of inorganic cements act as binders.

Concrete is an example of a large class of particulate composites composed of nonmetallic particles in a nonmetallic matrix. A few of the other classes of particulate composites include:

1 metals in metal,
2 metals in plastic,
3 ceramics and metal,
4 dispersion-hardened alloys, and
5 organic/plastic-inorganic.

Filler

Fillers used in large quantities to reinforce plastics are alumina (aluminum oxide), calcium carbonate, calcium silicate, cellulose flock, cotton (different forms), short glass fiber, glass beads, glass spheres, graphite, iron oxide powder, mica, quartz, sisal, silicon carbide, titanium oxide, and tungsten carbide. Choice of filler varies and depends to a great extent upon the requirements of the end item and method of fabrication.

Fillers offer a variety of benefits: increased strength and stiffness, reduced cost, shrinkage reduction, exothermic heat reduction, thermal expansion coefficient reduction, improved heat resistance, slightly improved heat conductivity, improved surface appearance, reduced porosity, improved wet strength, reduced crazing, improved fabrication mobility, increased viscosity, improved abrasion resistance, and/or impact strength. Fillers also can have disadvantages. They may limit the method of fabrication, inhibit cure of certain resins, and shorten pot life of the resin.

Property

They are strong, usually inert materials bound into a plastic to improve its properties such as strength, stiffness/modulus of elasticity, impact resistance, reduce dimensional shrinkage, etc. (Tables 15.2 and 15.6 and Figure 15.5). They include fiber and other forms of material. There are inorganic and organic fibers that have the usual diameters ranging from about one to over 100 micrometers. Properties differ for the different types, diameters, shapes, and lengths. As reviewed to be effective, reinforcement must form a strong adhesive bond with the plastic. For certain reinforcements such as glass special cleaning, sizing, etc. treatments are used to improve bonds.

Table 15.6 General properties of thermoset RPs per ASTM testing procedures

Reinforcing material	Specific gravity	Tensile Strength 10^3 psi	Tensile modulus 10^6 psi	Compressive strength, 10^3 psi	Flexural strength, 10^3 psi	Izod impact strength, ft-lb/in. notch	Heat resistance continuous, °F	Arc resistance, sec.
Polyester								
Glass cloth	1.5–2.1	30–70	1–3	25–50	40–90	5–30	300–350	60–120
Glass mat	1.3–2.3	20–25	½–2	15–50	25–40	2–10	300–350	120–180
Asbestos	1.6–1.9	30–60	1–3	30–50	50–70	2–8	300–450	100–140
Paper	1.2–1.5	6–14	½–1½	20–25	13–28	1–2	220–250	28–75
Cotton cloth	1.2–1.4	7–9	½–1½	23–24	13–18	1–4	230–250	70–85
Epoxy								
Glass cloth	1.9–2.0	20–60	2–4	50–70	70–100	11–26	330–500	100–110
Glass mat	1.8–2.0	14–30	1–3	30–38	20–26	8–15	330–500	110–125
Paper	1.4–1.5	10–19	½–1	20–28	19–24	½–1	260–300	30–100
Phenolic								
Glass cloth	1.8–2.0	40–60	1–3	35–40	65–95	10–35	350–500	20–130
Glass mat	1.7–1.9	5–20		17–26	10–60	8–16	350–500	400–150
Asbestos	1.7–1.9	40–65	2–5	45–55	50–90	1–6	350–600	120–200
Paper	1.3–1.4	8–20	1–2	20–40	10–30	⅓–1	225–250	Tracks
Cotton cloth	1.3–1.4	7–16	½–1½	30–44	14–30	½–3	225–250	Tracks
Nylon cloth	1.1–1.2	5–10	¼–½	28–36	9–22	2–4	150–165	Tracks
Silicone								
Glass cloth	1.6–1.9	10–35	1–2	25–46	10–38	5–13	400–700	150–250
Asbestos cloth	1.7–1.8	10–25	1–2	40–50	12–20	6–9	450–730	150–300

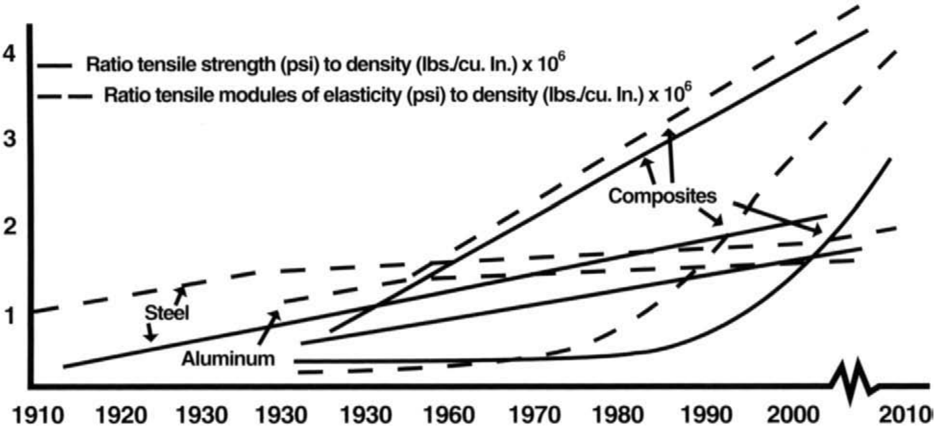


Figure 15.5 Reinforced plastics, steel, and aluminum tensile properties compared (courtesy of Plastics FALLO)

The glass content of a part has a great influence on its mechanical properties. In general, the more glass the more strength. This occurs with the ability to pack more reinforcement (Figure 15.6). Fiber content can be measured in percent by weight of the fiber portion (wt%). However, it is also reported in percent by volume (vol%) to reflect the better structural role of the fibers, that is related to volume (or area) rather than to weight (Figure 15.2). When content is only in percent, it usually refers to wt%.

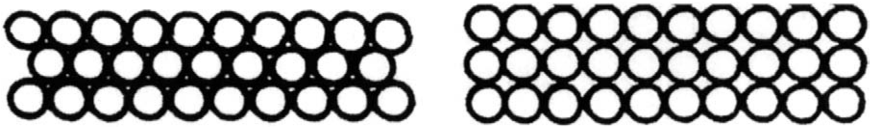


Figure 15.6 Fiber arrangements and property behavior (courtesy of Plastics FALLO)

The fiber content in mat or random fiber RPs is usually somewhat lower than for an isotropic laminate which is comprised of a number of unidirectional plies. Both laminates may, for example, be planar-isotropic. The random crisscross nature of chopped fibers in a mat does not permit close packing of the bundles, and thus the fiber content is usually low. With a lay-up of unidirectional plies, the packing of fibers within a ply may be very close, and the fiber content may be very high. The higher fiber content made from individual plies tends to make it stiffer and stronger than the mat construction.

There is a relationship between the way the glass is arranged and the amount of glass that can be packed in a given product. By placing continuous strands, such as round glass fibers in a filament winding pattern, next to each other in a parallel arrangement, more glass can be placed in a given volume (Figure 15.6). Glass content can range from 65 to 95.6 wt% or up to 90.8 vol%. When one-half of the strands are placed at right angles to each half, glass loadings range from 55 to 88.8 wt% or up to 78.5 vol%.

Special problems can arise from the use of RPs, due to the extreme anisotropy of some of them, the fact that the strength of certain constituent fibers is intrinsically variable, and because the test methods for measuring RPs' performance need special consideration if they are to provide meaningful values.

Some of the advantages, in terms of high strength-to-weight ratios and high stiffness-to-weight ratios, have been presented, which show that some RPs can outperform steel and aluminum in their ordinary forms. If bonding to the matrix is good, then fibers augment mechanical strength by accepting strain transferred from the matrix, which otherwise would break.[1] This occurs until catastrophic debonding occurs. Particularly effective here are combinations of fibers with plastic matrices, which often complement one another's properties, yielding products with acceptable toughness, reduced thermal expansion, low ductility, and a high modulus.

Orientation of reinforcement

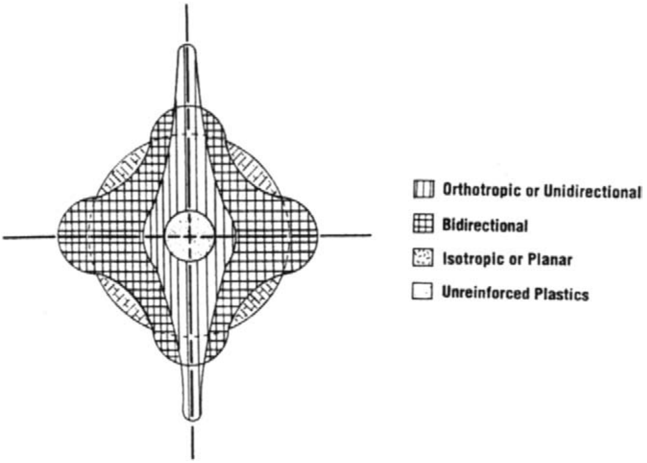
Both plastics and fibers influence orientation properties. For example, with certain TPs [including LCPs (Chapter 1)], the plastic's molecular orientation can be used to aid in increasing stiffness, strength, toughness, as well as craze and microcrack resistance in the direction of the plane or the plane of orientation.[450] A source of orientation is with fibers that cause positive and significant increased performance.

These effects are obvious in continuous filament winding. Not so obvious are the anisotropic materials properties resulting from many TP processes. Viscous melt flow of hot plastic into injection molds produces an oriented structure, usually having greater strength with crystalline TPs in the direction of flow than perpendicular to this direction. Shrinkage also is usually greatest with crystalline TPs perpendicular to the direction of flow. With amorphous TPs, greatest shrinkage can be in the direction of flow; however as in injection molding (IM), melt flow control can readily have even shrinkage in all directions. With fibers, shrinkage is less than unreinforced RPs (URPs) in the flow and perpendicular directions.

Flow within molds in processes such as IM and resin transfer molding (RTM), or through dies in the extrusion process, can orient the molecules of the resin as well as short or long fibers. This orientation can result in the designed properties desired or, if not properly processed, can result in inferior properties which may become evident in the form of reduced resistance to crazing, low impact strength, lowered creep rupture strength, etc.

The behavior of RPs is dominated by the arrangement and the interaction of the stiff, strong fibers with the less stiff, weaker plastic matrix. A major advantage is the fact that directional properties can be maximized. As reviewed in Table 15.7 they can be isotropic, bidirectional, orthotropic, etc. Woven fabrics that are generally directional in the 0° and 90° angles contribute to the mechanical strength at those angles. By the rotation of alternate layers of fabric to a lay-up of 0°, + 45°, 90°, and –45° alignment reduces maximum properties in the primary directions, but increases in the + 45° and –45° directions. Different fabric weave patterns are used to develop different property performances.

Table 15.7 Reinforcement orientation layup patterns



Hetergeneous/Homogeneous/Anisotropic

Heterogeneous identifies an RP that has properties that vary so that the composition varies from section to section in a heterogeneous mass that has uniform properties. For design purposes, many heterogeneous materials are treated as homogeneous (uniform). This is because a reasonably small sample of material cut from anywhere in the body has the same properties as the body. An unfilled (unreinforced) TP is an example of this type of material.

One must be aware that as the degree of anisotropy increases the number of constants or moduli required describing the material increases. With isotropic construction one could use the usual independent constants to describe the mechanical response of materials, namely, Young's modulus and Poisson's ratio.

RPs are either constructed from a single layer or built up from multiple layers. The properties of each layer are usually orthotropic, which is a special case of anisotropy. Fibers that remain straight in the single layer are desired. However, with many fabrics, they are woven into configurations that kink the fiber bundles severely. Such fabric constructions may be very practical since they drape better over doubly-warped molds than do fabrics that contain predominantly straight fibers.

There are fiber bundles in lower cost woven roving that are convoluted or kinked as the bulky rovings conform to a square weave pattern. Kinks produce repetitive variations in the direction of reinforcement with some sacrifice in properties. Kinks can also induce high local stresses and early failure as the fibers try to straighten within the matrix under a tensile load. Kinks also encourage local buckling of fiber bundles in compression and reduce compressive strength. These effects are particularly noticeable in tests with woven roving, in which the weave results in large-scale convolutions. Regardless, extensive use of fabrics is made based on their capabilities.

Material of construction

Reinforcements can be in continuous forms (fibers, filaments, woven or non-woven fabrics, tapes, rovings, etc.), chopped forms having different lengths, or discontinuous in form (flakes, whiskers, spheres, etc.). The reinforcements can allow the RP materials to be tailored to the design, or the design tailored to the material.[4, 173, 210]

Certain fibers such as glass should go through binder/sizing coupling agent treatments to maximize their bonding capabilities and, very important, protection of brittle fibers. A major requirement for these agents involves the proper handling of the glass fibers during their treatment. Continuous glass fiber (as well as other fiber) intended for weaving are usually treated at their forming bushing during their manufacture with starch-oil binders.

Protecting the fibers from damage is by a binder lubrication during their formation and such subsequent textile operations as twisting, plying, and weaving. Usually they are satisfactory when used with certain thermoplastics but are not compatible with thermoset plastics. As an example the hydrophilic character of the binders allows moisture to penetrate the glass-plastic interface, which leads to degradation of RTPs or RTSs in wet and humid environments.

The binder is removed prior to applying sizing agents via heat treatment before being used with these plastics. This is accomplished by exposing the reinforcing material (fiber, fabric, etc.) to carefully controlled time-temperature cycles. To protect the weak heat-cleaned fibers, chemical sizing coupling agents are used such as methacrylic chromic chloride complex, organosilanes, etc.

Prepreg

Prepregs are used to mold different products. It is a term used for a reinforcement preimpregnated usually with a TS polyester liquid resin. Different forms of reinforcements are used (nonwoven mat, woven fabric, braided, preform, roving, etc.). The catalyzed compounded resin is impregnated into the reinforcement and partially cured to a tack-free state in the B-stage (Chapter 1). The reinforcement can be predesigned to meet performance requirements. The molder uses the prepreg in a compression mold or other molding process that will allow the required temperature and pressure conditions to be met, based on how the resin was compounded. With proper storage condition of temperature [at least about 21C (70F)], their shelf life can be controlled; lasting at least 6 months.[441]

Methods for locating and orienting them onto a molding surface, in accordance with an RP design pattern, are adapted to the tack and drape characteristics of the prepreg. The woven fabrics make possible use of sewn stitches, staples, or clamps. Usually, the lay-ups are enlarged to provide allowances for trimming after the RP has been cured. Sometimes they are draped over male forms with weighted edges to draw the lay-ups snugly onto the molding surface prior to final cure. Very often, successful lay-ups depend on the operators' skills to innovate. In England the National Physical Laboratory (NPL) is preparing a prepreg standard qualification plan (SQP) that will provide a Good Practice Guide (GPG).[467]

Sheet Molding Compound

SMC is a ready-to-mold material representing a special form of a B-stage prepreg. From the original development of the thin or single-ply prepregs, the thicker SMC was developed. SMC is a ready-to-mold material representing a special form of a prepreg. It is usually a glass fiber-reinforced TS polyester resin compound in sheet form. The sheet can be rolled into coils during continuous processing. SMC is basically made by mixing and metering the compound, feeding the glass-roving reinforcement, wetting out the glass fibers, rolling up the sheet, and allowing the material to mature. A plastic film covering separates the layers to enable coiling and to prevent contamination, sticking, and monomer evaporation. This film is removed before the SMC is charged into a mold such as matched-die molding or compression molding.

This moldable material primarily consists of TS polyester resin, glass fiber reinforcement, and filler. Additional ingredients, such as low-profile additives, cure initiators, thickeners, and mold-release agents are used to enhance the performance or processing of the material. As with any material, such as metallics and plastics, SMC can be formulated in-house or by compounders to meet performance requirements of a particular application such as tensile properties or Class A surface finish. Varying the type and percentage of the composition will result in variations in mechanical properties and processability.

Prior to SMC being used for molding it must age or mature. This maturation time is required to allow the relatively low-viscosity resin to chemically thicken. The thickened SMC is easier to handle and prevents the paste from being squeezed out of the glass fiber sheet during processing. Typically SMC requires about three to five days to reach the desired molding viscosity.

This compound usually consists of additional ingredients such as low-profile additives, cure initiators, thickeners, and mold-release agents. They are used to enhance the performance or processing of the material. SMC can be formulated in-house or by compounders to meet performance requirements for a particular application such as tensile properties and/or Class A surface finish. Different methods are used to produce SMCs that provide different properties and performances.[10, 12]

Bulk Molding Compound

BMC also called dough molding compound (DMC) is a mixture usually of short glass fibers, resin, and additives similar to the SMC compound. This mixture can be produced in bulk form, or extruded in rope-like form (called a log) for easy handling. It is available in different combinations of resins, usually TS polyesters, additives, and reinforcements. They meet a wide variety of end-use requirements in high-volume applications where fine finish, good dimensional stability, part complexity, and good overall mechanical properties are important.

Usual method of molding BMC is by compression molding. BMCs can also be injection molded in much the same way as other plastic compounds using ram, ram-screw, and, for certain BMC mixes, conventional reciprocating screw injection molding techniques (Chapter 4).

The usual BMC plastic uses thermoset polyester. Bulk Molding Compounds Inc. (BMCI) in West Chicago, IL, the largest USA maker of BMC materials has come out with phenolic-based compounds. New BMC-X-Cel is aimed at higher-temperature uses such as automotive under-hood and exhaust components as well as fuel cells and appliances. Glass-filled phenolic BMC maintains more than 85% of its ambient properties at 200C (392F) and more than 60% at 300C (572F). BMC-X-Cel cures in about a minute at 300 to 370F (149 to 188C) and requires a postbake of 20 minutes up to 2 hr at 350F (177C), depending on the ultimate properties desired.

Compound

In addition to thermoset reinforced compounds there are many TPs reinforced compounds using plastics such as polycarbonate, nylon, polypropylene, polystyrene, polyurethane, acetal, polyester-TP, and polyimide. They are usually compounded with some type of additive, filler, and/or plastic blend with reinforcements that are usually short, chopped, or milled glass fiber.[210] Commercial RTP compounds are available in several forms: pellets for injection molding or extrusion, unidirectional tape for filament winding and similar applications, sheets for stamping and compression molding, bulk compounds for compression molding, etc. Reinforcements significantly improve or modify mechanical properties, whereas fillers can basically reduce cost, etc.

Nonfibrous reinforcements are also employed as reinforcements and fillers. They result in increased tensile strength and deflection temperature, but usually decrease impact resistance. Nonfibrous reinforcements are preferred when fabricating with exceptional flatness. The nonfibrous include mica, glass beads, and minerals such as wollastonite (talc, calcium carbonate, and kaolin are considered fillers). Unlike fibrous reinforcements the nonfibrous reinforcements can be processed by many different technologies.

There are also flexible RP. These RTP elastomeric materials provide special engineered products such as conveyor belts, mechanical belts, high temperature or chemical resistant suits, wire and cable insulation, and architectural designed shapes.

Fabricating process

Different processes are used. About 5wt% of all plastic products produced worldwide are RPs. Injection molding consumes over 50wt% of all RP materials with practically all of it being thermoplastics (Chapter 4).

The different processes range in fabricating pressures from zero (contact), through moderate, to relatively high pressure [2,000 to 30,000 psi (13.8 to 207 MPa)], at temperatures based on the plastic's requirements that range from room temperature to over room temperatures. Equipment may be low cost to rather expensive specialized computer control of the basic machine with auxiliary equipment. In turn labor costs range from very high for low cost equipment to very low for the high cost equipment.[445]

Each process provides capabilities such as meeting production quantity (small to large quantities and/or shapes), performance requirements, proper ratio of reinforcement to matrix, fiber orientation, reliability/ quality control, surface finish, materials used, quantity, tolerance, time schedule, and so forth versus cost (equipment, labor, utilities, etc.). There are products when only one process can be used but there can be applications where different processes can be used.

Preform Process

The preform process has been used since the 1940s. As time passed significant improvements occurred processing-wise, equipment-wise, plastic-wise, and cost-wise. This is a method of making chopped fiber mats of complex shapes that are to be used as reinforcements in different RP molding fabricating processes rather than conventional flat mats that may tear, wrinkle, or give uneven glass distribution when producing complex shapes in a mold. Most of the reinforcement used is glass fiber rovings. They are desirable where the product to be molded is deep or very complex shapewise. Oriented patterns can be incorporated in the preforms. Different methods are used with each having many different modifications. They include a plenum chamber, directed fiber, and water slurry.

The rovings in a plenum chamber are fed into a cutter and after being cut to the desired lengths, fall either into a plenum chamber or perforated screen where the air is exhausted from under the screen. A plastic binder of usually up to 5wt% is applied and is later cured. As the glass falls into the plenum chamber, the air flow pattern and baffles inside the screen control its distribution. Preform screen rotates and sometimes is tilted to ensure maximizing uniform deposits of the roving.

With the directed fiber system strands are blown onto a rotating preform screen from a flexible hose. Roving is directed into a chopper where air flow moves it to a preform screen. Use can be made of a vertical or horizontal rotating turntable. This process requires a rather high degree of skill on the part of the operator; however, automated robots are used to provide a controlled system producing quality preforms.

With water slurry chopped strands are in water (similar to that used by the paper pulp industry for centuries). It produces intricate shaped preforms that are tough and self-supporting. Bonding together the preform can use cellulose fibers and/or bonding resins. Where maximum strength is not required, the cellulose content can be sufficiently high. The fibers can be dyed during the slurry process.

The correct manufacture of the screen is important for success. Different shapes can be used to meet different product designs. Recognize that cylindrical preforms are easier and less costly to produce than box-like sections. Also it is important to recognize that during the rotation of a cylindrical part, the fibrous glass will flow uniformly onto the screen because most sections move at a uniform linear rate. With a rectangular section it is difficult because the comers rotate in a wider circle than do the center sections and because the air flow is lowest at the corners. Contouring the box shape can improve reinforcement distribution.

Preform screens are usually made from 16-gauge perforated material with ⅛ in. holes on $^{3}/_{16}$ in. centers. This produces about 40% open area. For some operations, a more open area is required. Perforation patterns are also used to develop specifically designed reinforcement directional properties. The screen is usually designed so that the outside contour is identical with the contour of the mating half of the mold. A screen which is not of the correct size will cause a great deal of difficulty in the molding operation. If the screen is too small, the preform will tear during the molding. If too large, wrinkling and overlapping of the preform will result.

The preform is usually heavy on the flat top and light on the edges and corners. Internal baffles may be added in the preform screen to control the airflow, thus giving a more uniform deposition of glass. The exact area of the baffle usually has to be worked out on a trial-and-error basis until experience is developed. Close cooperation with the preform-machine manufacturer is helpful.

When molding a product with a variable wall thickness, it is possible to vary the thickness of the preform. This is usually accomplished by baffling. Another approach that can be used is to completely block off areas where no fiber is desired. This action saves material that would otherwise be trimmed off and probably discarded. It has also proven practical to combine two or more preforms into one molded part. This technique is very useful where the thickness of the molded part prohibits the collection of the preform in one piece.

Conventional Process

The more conventional processes used for unreinforced plastics also use RPs. They include those reviewed in this book – namely injection molding (IM), extrusion (EX), thermoforming (TF), foaming, calendering, coating, casting, reaction injection molding (RIM), rotational molding (RM), compression molding (CM), reaction injection molding, rotational molding, and others (Chapters 4 to 14 and 16). These processes are usually limited to using short reinforcing fibers however there are processes that can use long fibers.[210] Since glass fibers are extensively used, specifically in IM, the glass fibers will cause wear of metals during processing such as plasticating barrels and molds or dies. Using appropriate metals that can provide a degree of extending their operating time can reduce this wear (Chapter 17). Information on processes used to fabricate RP products follows.[37, 292, 293]

Compression Molding

TS plastics in reinforced sheets and compounds are usually used. Also used are reinforced thermoplastic sheets and compounds. With TSs compression molding (CM) can use preheated material (dielectric heater, etc.) that is placed in a heated mold cavity. The mold is closed under pressure causing the material to flow and completely fill the cavity. Chemical crosslinking occurs solidifying the TS molding material.

The closed mold shapes the material usually by heat and pressure. With special additives the TS material can cure at room temperature. It would have a time limit (pot life) prior to curing and hardening. Based on the compound's preparation, sufficient time is allowed to store and handle the compound prior to its chemical reaction curing action occurring (Chapter 14).

Depending on what plastic is being molded, the clamping force may be from contact to over thousands of tons. TS polyesters usually have just contact pressure. There are plastics requiring pressure. A force is also required to open the mold that is usually much less than the clamping force. So one has to ensure that available opening clamping pressure is obtainaable. Usually this requirement is not a problem. Clamping predominantly use hydraulic systems. Also becoming popular are all electric drive systems and/or with hydraulic/electrical hybrid systems. The actual mechanical mechanisms range from toggle to straight ram systems. Each of these different systems has their individual advantages (Chapter 4).

The mold is fastened on the platens. These platens usually include a mold-mounting pattern of bolt holes or "T" slots; standard pattern is recommended by SPI. Platens range from the usual parallel design to other configurations meeting different requirements. The parallel type can include one or more floating platens located between the stationary and normal moveable platens resulting in two or more daylight openings where two or more molds or flat laminates can be used simultaneously during one machine operating cycle.

There are presses that include shuttle (molds in which usually two, or more, are moved so that one mold is positioned to receive material and then moves to the press permitting another mold to receive material with this cycle repeating; result is to permit insert molding, reduce molding cycle, etc.), rotary or carousal system, and "book" opening or tilting press.[4, 279]

Applying vacuum in a mold cavity can be very beneficial in molding plastics at low pressures. Press can include a vacuum chamber around or within the mold providing removal of air and other gases from the cavity(s).

Flexible Plunger

This process is a take-off from compression molding that uses solid material male and female matching mold halves. This unique process uses a precision-made, solid shaped heated cavity and a flexible plunger that is usually made of hard rubber or TS polyurethane. This two-part system can be mounted in a press, either hydraulic or air-actuated. Rather excellent product qualities are possible at fairly low production rates. The reinforcement can be positioned in the cavity and the liquid TS resin is poured on it. Also used are prepregs, BMC, and SMC.

The plug is forced into the cavity and the product is cured. The plunger is somewhat deeper and narrower than the cavity. It is tapered in such a manner that contact occurs first in the lowest part of the mold.

Ultimate pressure usually used is up to 400 to 700 kPa (58 to 100 psi) in the plunger, this causes the contact area to expand radially toward the rim of the cavity, thereby forcing the resin and air ahead of it through the reinforcement with the target of developing a void free product. The pressure conforms to irregularities in the lay-up, permits wall thickness to be varied within reasonable limits, and makes a good surface possible against a metal mold surface. The fact that the heat can be applied only from the cavity side leads to long cure cycles, but the same factor tends to produce resin richness, and consequently greater smoothness on the outside of the molding.

Flexible Bag Molding

An air inflated-pressurized flexible-type envelope can replace the plunger. This process provides higher glass content and decreases chance of voids. Limitations include extensive trimming and only one good surface.

Laminate

This refers to many different fabricated RP products such as high or contact/low pressure laminates. It usually identifies flat or curved panels using high pressure rather than contact or low pressure. It is a product made by bonding together two or more layers of laminate materials. The usual resins are thermoset such as epoxies, phenolics, melamines, and TS polyesters. A modification of this process uses TPs. The type of materials can be endless depending on market requirements. Included are one or more combinations of different woven and/or nonwoven fabrics, aluminum, steel, paper, plastic film, etc.

High pressure laminates generally use pre-loaded (prepreg) RP sheets in a hot mold at pressures in excess of 7 MPa (1015 psi). Compression multi platen presses are used; up to at least 30 platens producing the flat (also curved) sheets at high production rates. Laminates are molded between each platen simultaneously. Automatic systems can be used to feed material simultaneously between each platen opening and in turn after curing and the multiple platens open cured products are automatically removed. The contact or low pressure laminates use prepregs that cure at low pressures such as TS polyester resins. Depending on the resin formulation just contact pressure is only required such as using hand operated rollers. The usual highest pressure that identifies low pressure laminates is at 350 kPa (50 psi).

In the industry, for almost a century these laminates are used for their electrical properties, impact strength, wearing qualities, chemical resistance, decorative panels, or other characteristics depending on fiber-resin used with or without a surfacing material. They are used for printed circuit boards, electrical insulation, decorative panels, mechanical paneling, etc. The major change in the process about a half-century ago was making the operation completely automatic, this significantly reduced labor cost.

Hand Lay-Up

This low cost process has different names such as open, contact, or bag molding (due to different market uses at times different processing names are used that overlap a process). It is a very simple and most versatile process for producing RP products. However, it is slow and is usually very labor intensive. It consists of hand tailoring and placing of layers of (usually glass fiber) fibrous reinforcements either random oriented mat, woven roving, or fabric on a one-piece mold and simultaneously saturating the layers with a liquid plastic (usually TS polyester) (Figure 15.7). Usually it is required to coat the mold cavity with a parting agent. Gel coatings with or without very thin woven or mat glass fiber scrim reinforcement are also applied to provide smooth and attractive surfaces. Molds can be made of inexpensive metal, plaster, RP, wood, etc. (Chapter 17).

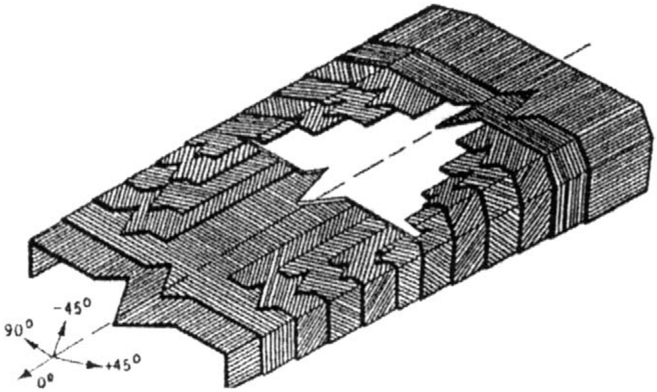


Figure 15.7 Layout of reinforcement is designed to meet structural requirements

Depending on the resin preparation, the material in or around a mold can be cured with or without heat, and commonly without pressure. Curing needs include room temperature conditions, heat sources, vacuum bags, pressure bags, autoclaves, etc. An alternative is to use preimpregnated, B-stage TS polyester or sheet molding compound (SMC), but in this case heat is applied with low pressure via a impermeable sheet over the material. This process can produce compact structures that meet tight thickness tolerance simulating injection molded products.

Generally, the process only requires low-cost equipment that is not automated. However, automated systems are used. Automation includes cutting and providing the layout of the cut prepreg in a mold. In turn, the designed RP assembly is delivered to a curing station such as an oven or autoclave.

This process can be recommended for prototype products, products with small to large production runs, molding very large and complex products, and products that require high strength and reliability. The size of the product that can be made is limited by the size of the curing oven. However, outdoor UV via outdoor sunlight curing or room temperature curing plastic systems permits practically unlimited product size. Alternate curing methods are used that include induction, infusion (vacuum-pressure), dielectric microwave, xenon, UV, electron beam, or gamma radiation.

The general process of hand molding can be subdivided into specific molding methods such as those that follow. The terms of some of these methods as well as others reviewed here overlap the same technology; the different terms are derived from different sections of the RP and other industries.

Vacuum Bag Molding

This process also called just bag molding. It is the conventional hand lay-up or spray-up that is allowed to cure without the use of external pressure. For many applications this is sufficient, but maximum consolidation may not be reached. There can be some porosity; fibers may not fit closely into internal corners with sharp radii but tend to spring back. Resin-rich and/or resin-starved areas may occur because of draining, even with thixotropic agents. With moderate pressure (hand rollers, etc.) these defects or limitations can be overcome with significant improvement in mechanical properties.

One way to apply such moderate pressure is to enclose the wet-liquid resin material and mold in a flexible membrane or bag, and draw a vacuum inside the enclosure. Atmospheric pressure on the outside then presses the bag or membrane uniformly against the wet lay-up. An effective pressure of 69–283 kPa (10 to 14 psi) is applied to the product. Air is mechanically worked out of the lay-up by hand usually using serrated rollers. The vacuum directly helps to remove air in the wet lay-up via techniques such as using bleeder channels within the bag (using material such as jute, glass wool, etc.) to aid in the removal of air and also to permit drainage of any excess resin. This layup is than exposed to heat using an oven or heat lamp.

Vacuum Bag Molding and Pressure

To maximize properties in the product, higher pressure is needed in the conventional vacuum bag system. A second envelope can be placed around the whole assemblage. Air under pressure is admitted between the inner bag and the outer envelope after the initial vacuum cycle is completed. Still higher uniform pressures can be obtained by placing the vacuum assemblage in an autoclave. By this technique, an initial vacuum may or may not be employed. Using an autoclave assures good results.

Pressure Bag Molding

This process is used when more pressure is required than those processes just reviewed. A second envelope (or structure) is placed around the whole assemblage and air pressure admitted between the inner bag and outer envelope, or between the inner bag and structure. Application of pressure (air, steam, or water) forces the bag against the product to apply pressure while the product cures. Using this combination of vacuum and pressure bags results in ease of air or gas removal and higher pressures resulting in more densification.

Autoclave Molding

Very high pressures can be obtained for processing RPs by placing a pressure or vacuum bag molding assemblage in an autoclave. This curing process may or may not employ an initial vacuum. Some of the different RP processes are used in conjunction with the use of an autoclave oven. Hot air or steam pressures of 0.36 to 1380 MPa (50 to 200 psi) is used. The higher pressure will yield denser products. If still higher pressures are required (avoid this approach unless you have considered the danger of extremely high pressures), a hydroclave may be used, employing water pressures as high as 70 MPa (10,150 psi). The bag must be well sealed to prevent infiltration of high pressure air, steam, and/or water into the molded product. In all these approaches, the fluid pressure adjusts to irregularities in the lay-up and remains effective during all phases of the resin cure, even though the resin may shrink. Use of this process includes seamless containers, tanks, pipes, etc.

Autoclave Press Clave

This process simulates autoclave by using the platens of a press to seal the ends of open chamber. It provides both the force required to prevent loss of the pressurized medium and the heat required to cure the RP inside.

Wet Lay-Up

This procedure is usually just called bag molding. It is a method that is sometimes combined with bag molding to enhance the properties. Because it is difficult to wet out dry fibers with too little resin, initial volumetric fraction ratios of resin to fiber are seldom less than 2:1. On a weight basis the ratio is about 1:1. Liquid catalyzed resin is hand-worked or automatically worked into the fibers to ensure wet-out of fibers and reduce or eliminate entrapped air.

Bag Molding Hinterspritzen

This patented process allows virgin or recycled thermoplastics such as PP, PC/ABS, etc. to thermally bond with the backing of multilayer PP based fabrics providing good elasticity. This one step molding technique provides a low cost approach for in-mold fabric lamination that range from simple to complex shapes.

Contact Molding

Also called open molding or contact pressure molding. It is a process for molding RPs in which the reinforcement and plastic are placed in a mold cavity. Depending on the plastic used, cure is either at room temperature using a catalyst-promoter system or by heating in an oven without pressure or using very little (contact) pressure. Contact molding gave rise to bag molding, hand lay-up or open-mold, and low-pressure molding. It plays a significant role in molding RPs. It is difficult to surpass if a few products are to be made at the lowest cost. The process is basically what was reviewed for Bag Molding.

Filament Winding

Filament winding (FW) is a fabrication technique for forming reinforced plastic parts of high strength/modulus and lightweight. It is made possible by exploiting the remarkable strength properties of their continuous fibers or filaments encased in a matrix of a resinous material. For this process, the reinforcement consists of filamentous non-metallic or metallic materials processed either in fibrous or tape forms.[488, 489]

Frequently used is some form of glass: continuous filaments roving, yarn, or tape. The glass filaments, in whatever forms are encased in a plastic matrix, either wetted out immediately before winding (wet process) or impregnated ahead of time (preimpregnated process). The plastic fundamentally contains the reinforcement, holding it in place, sealing it from mechanical damage, and protecting it from environmental deterioration. The reinforcement-matrix combination is wound continuously on a form or mandrel whose shape corresponds to the inner structure of the part being fabricated. After curing of the matrix, the form may be discarded or it may be used as an integral part of the structural item.

Reinforcements have set pattern lay-ups to meet performance requirements (Figure 15.8). Target is to have them uniformly stressed.

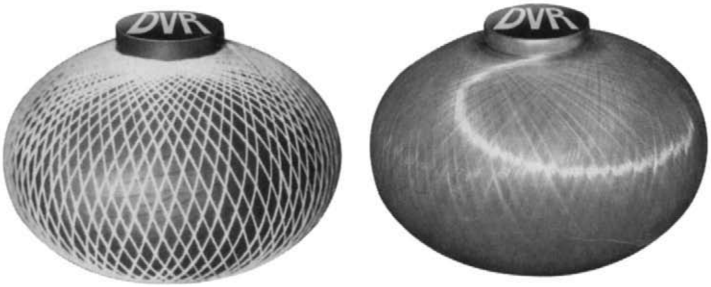


Figure 15.8 Views of fiber filament wound isotensoid pattern of the reinforcing fibers without plastic (left) and with resin cured

In winding cylindrical pressure vessels, tanks, or rocket motors, two winding angles are generally used. One angle is determined by the problem of winding the dome integrally with the cylinder. Its magnitude is a function of the geometry of the dome. These windings also pick up the longitudinal stresses. The other windings are circumferential or 90° to the axes of the case and provide hoop strength for the cylindrical section.

It is possible to wind domes with a single polar port integrally with a cylinder comparatively easily without the necessity of cutting filaments. Cutting is obviously not desirable, since it interrupts the continuity of the basically orthotropic material. The usual procedure in winding multiported domes is to add interlaminate reinforcements during the winding operation where the ports are to be located.

It is possible to wind integrally most of the bodies of revolution, such as spheres, oblate spheres, and torroids. Each application, however, requires a study to insure that the winding geometry satisfies the membrane forces induced by the configuration being wound.

FW can be carried out on specially designed automatic machines. Precise control of the winding pattern and direction of the filaments are required for maximum strength, which can be achieved only with controlled machine operation. The equipment in use permits the fabrication of parts in accordance with properly designed parameters so that the reinforced filamentous wetting system is in complete balance and optimal strength is obtained. The maximum strength is achieved when filaments in tension carry all major stresses. Under proper design and controlled fabrication, hoop tensile strengths of filament wound items can be achieved of over 3,500 MPa (508,000 psi), although strength of 1,500 MPa (218,000 psi) is more frequently achieved.

Since this fabrication technique allows production of strong, lightweight parts, it has proved particularly useful for components of structures of commercial and industrial usefulness and for aerospace, hydrospace, and military applications. Both the reinforcement and the matrix can be tailor-made to satisfy almost any property demand. This aid in widening the applicability of FW to the production of almost any item wherein the strength to weight ratio is important. FW is used in different shapes such as the usual circular and elliptical shape to produce rectangular shapes.

FW structures present certain problems because of the lack of ductility in the glass reinforcement. These can be partially solved by proper design and fabrication procedures. Reinforcements other than glass can be used to obtain good ductility, but some of these have lower temperature strength and characteristics. Proper construction constitutes a well-proved means of utilizing an intrinsically nonductile reinforcement to obtain a high degree of confidence in the structural integrity of the end product. Since glass has high strength and is a relatively low-cost product, glass filaments are still the major reinforcing material. Other filaments for applications requiring properties such as higher temperatures or greater stiffness include quartz, carbon, graphite, ceramics, and metals alone or in combinations that include glass fibers.

A further difficulty with the basic materials is that they do not lend themselves readily to simple concepts and to simple comparisons. The matrix components are essentially the same plastics as those used for conventional reinforced plastic laminates. Epoxy plastics are more widely used than others, although phenolics and silicones give structures with higher temperature properties. Thermoset polyesters are used for many commercial structures in which cost is a problem and high temperatures do not prevail.

For certain FW vessels the low modulus of elasticity of the glass-plastic material is a serious disadvantage. Only moderate improvements in modulus of elasticity by modifications in glass composition or in processing tend to be feasible. Any significant improvement in modulus of elasticity requires changes in the glass composition. There are effective additives to the glass to increase its modulus without proportional increase in density such as beryllium oxide.

Interlaminar shear constitutes possible limitations on FW parts. Although the absence of interweaving (such as fabrics) boosts tensile strength by eliminating cross fraying, shear strength is limited by the bonding of the reinforcement to the plastic. In conventional woven cloth laminates, the high points of one layer tend to interlock with the low points of adjacent layers. This results in strengthening of the composite against shear failure. Compared to other plastics or matrices epoxy gives better interlaminar shear because of its inherently better bonding. By proper design, the low values of interlaminar shear can be minimized.

FW structures have lower ultimate bearing strengths than conventional laminates, for they are more rigid and less ductile. Accordingly, they have less ability to absorb stress concentrations around holes and cut-outs. The original higher tensile strength permits allowable design stresses under these conditions. Since cutting, drilling, or grooving for attachments or access openings reduce the high mechanical strength of filament wound structures, proper design is necessary. Damaging machining operations are to be avoided after final curing of the part. Destructive "cut-outs" or attachment holes are to be eliminated by incorporating the use of premolded plastic or metal inserts into the designs.

Techniques cannot be used for every structural element. The shape of the part must permit removal of the winding mandrel after final curing. Reversed curvatures should be eliminated whenever possible, since it is difficult to wind them and hold the filaments under tension. In order to meet this problem, fusible, expandable, and multiparty mandrels are often required.

The cost of FW parts is low only when volume production is achievable. Manufacturing processes should be mechanized and completely automated to obtain, by extensive and careful tooling, the close tolerances which are required in filament wound structures to meet high-strength but low-cost objectives. Precision winders with carefully selected mandrels and speed controls, special curing ovens, and matched grinders are required. It takes time to develop this equipment, and a high initial investment is necessary. Once the original tooling cost has been amortized, the unit cost of individual filament wound parts becomes relatively low, since the basic materials have a low cost.

Fabricating RP Tank

Classical stress analysis proves that hoop stress (stress trying to push out the ends of the tank) is twice that of longitudinal stress. To build a tank of conventional materials (steel, aluminum, etc.) requires the design to use sufficient materials to resist the hoop stresses that result in unused strength in the longitudinal direction. In RP, however, the designer specifies a laminate that has twice as many fibers in the hoop direction as in the longitudinal direction.[1]

Injection Molding

As reviewed over 50wt% of all RPs go through conventional injection molding machines (IMMs). Practically all thermoplastics are used. Both short and long glass and other fibers are injection molded. The RP compounds that are thick and pasty (BMC, etc.) are principally processed through ram IMMs with some going through screw IMMs (Chapter 4).

Marco Process

During the 1940s to 1960s this process was extensively used to fabricate many different RP products. It was the take-off for resin transfer molding (RTM) and bag molding (BagM). Reinforcements are laid up in any desired pattern as in RTM and BagM. Low cost matched molds (wood, etc.) confine the reinforcement. In this process the usual liquid catalyzed TS polyester surrounds the mold in its open trough (Figure 15.9). From a central opening (hole) in one of the mold halves a pressure is applied so that the plastic flows through the reinforcements. With proper wet-out of fibers voids are eliminated.

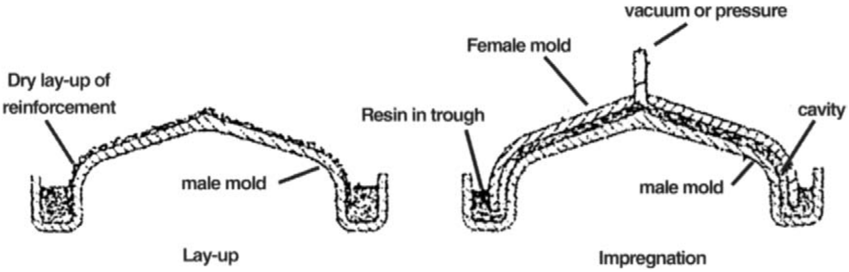


Figure 15.9 Use is made of vacuum, pressure, or pressure-vacuum in the Marco process

This method when first used was the reverse of RTM. By 1960 the Marco method used vacuum pressure at the parting line and also used a vacuum for a push-pull action where pressure was applied in the center hole similar to what is now used in RTM. Pressure was applied through the center hole alone or in a combination with a vacuum from the trough area to aid the flow of the liquid plastic.

Pultrusion

This process can produce products that meet very high structural requirements, high weight-to-strength performances, electrical requirements, etc. It is a continuous process for fabricating RPs that usually have a constant cross sectional shape (I-, U-, H-, and other shapes). The reinforcing fibers are pulled through a plastic (usually TS) liquid impregnation bath through rollers, etc. and then through a shaping die followed with a curing action. The material most commonly used is TS-polyester with glass fiber. Other plastics, such as epoxy and polyurethane are used where their improved properties are needed. When required, fiber material in mat or woven form is added for cross-ply properties.

There are also systems eliminating the plastic bath so that the plastic is impregnated in the die. This approach is a take-off in extruding wire and cable coating systems providing controlled impregnation (Chapter 5). Cleverly designed die have been used that include rotating sections providing complex pultruded products.

In contrast to extrusion, in this process a combination of liquid plastic and continuous fibers (or combined with short fibers) is pulled continuously through a heated die of the shape required for continuous profiles. Glass content typically ranges from 25 to 75wt% for sheet and shapes, and at least 75% for rods. RP shapes include I-beams, L-channels, tubes, angles, rods, sheets, etc.

Reactive Liquid Molding

Reactive liquid molding (RLM) proceeds in two steps: (1) preform formation by organizing loose fibers into a shaped preform, and (2) impregnation of the fibers with a low viscosity reacting liquid. Heat transfer in the mold may thermally activate the reacting material or mixing activated by impingement of two reactive streams as in the polymerization of polymers (Chapter 1). Simulations of flow and reaction, a relatively recent innovation in RLM, allow determination of vent and weld line locations, fill times, and control of racetracking in terms of gate locations when injected molded, mat permeability, and processing conditions. Commercial success requires (1) fast reaction and (2) efficient preform formation. Using higher mold temperatures and preheating the preform can decrease cycle time for thermally active systems. Low pressure and temperature processing by RLM allow the use of inexpensive lightweight tools, especially for prototyping. RLCM allows customizing reinforcement to give desired local properties and part consolidation via complex 3D geometries.

Resin Transfer Molding

Resin transfer molding (RTM) includes the use of reinforcements (RRTM). It is a closed mold, low-pressure process in which a preplaced dry reinforcement fiber construction (such as woven and nonwoven fabric or a fiber preform) with or without decorative surface material is impregnated with a liquid plastic through an opening in the center area of a mold (Figure 15.10). The resin at about 50 psi (0.3 MPa) pressure moves through the reinforcement located in the mold cavity. The air inside the cavity is displaced by the advancing resin front, and escapes through vents located at the high points or the last areas of the mold to be filled. When the mold has filled, the vents and the resin inlet(s) are closed. After curing via room temperature hardeners and/or heat, the part is removed. This process provides a rather simple approach to molding designed RP parts in relatively low-cost molds (using low pressure), and the molds are manufactured in a short time.

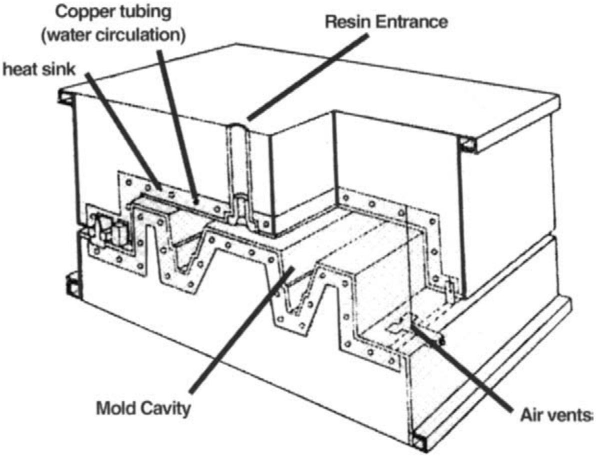


Figure 15.10 Cut away example of a mold used for resin transfer molding

Rotational Molding

In rotational molding (RM), a solid (powder or pellet) or liquid with or without reinforcing fibers and principally TPs are used (Chapter 13). With reinforcement is is called RRM. Reinforcement is placed in a mold that only has a cavity to form the outside of the part to be made. The mold is rotated simultaneously about two axis at similar or different speeds depending on the part configuration. The material is forced against the walls of the cavity. It first goes through a heating period to melt the plastic followed by a cooling period to solidify the plastic. Small to large parts are molded. Because they are not subjected to pressure, relatively low cost molds can be used.

Squeeze Molding

This method is a take off between RTM and hand lay-up. The reinforcement and a room temperature curing TS polyester resin are put into a mold. In turn, the mold is put into an air pressure bag where the resin is slowly forced through the reinforcement in the mold cavity at low pressures of about 200 to 500 kPa (30 to 75 psi). The RP is cured at room temperature in unheated molds. It is a slow process so one or a few products per day are usually molded.

Infusion Molding

RTM can also incorporate vacuum to assist plastic melt flow. With vacuum-assisted RTM the process is called infusion molding.[300] This process could be identified as a take-off to the Marco process.[3]

SCRIMP Process

The Seeman Composites Resin Infusion Process (SCRIMP®) is a gas-assist resin transfer molding process. Glass fiber fabrics/thermoset vinyl ester polyester plastic and polyurethane foam panels (for insulation) are usually used. They are placed in a segmented tool. A vacuum is pulled with a bag so that a huge amount of plastic can be drawn into the mold. It is similar to various reinforced plastics molding processes. It is adaptable to fabricating large RP products such as a transportation bus weigh about 10,000 kg (22,000 lb) that is 3200 kg (7000 lb) lighter than steel units.

Soluble Core Molding

This technology is also called fusible core, soluble core technology (SCT), lost-wax, loss core, etc. molding. This technique is a take off and similar to the lost wax molding process used during the ancient Egyptian times fabricating jewelry. In this process, a core is usually molded of a low-melting-point eutectic alloy (zinc, tin), water-soluble TP, wax formation, etc. During core installation, it can be supported by the mold core pins, spiders, etc. The core is inserted in a mold (IM, CM, casting, etc.) and plastic injected or located around the core. When plastic has solidified and is removed from the mold, the core is removed by melting at a temperature below the plastic melting point through an existing opening or will require drilling a hole in the plastic.

Lost-Wax Process

When this soluble fusible core molding technique was first used it involved a bar of wax wrapped with RPs (such as glass fiber-TS polyester resin). After the RP is cured (bag molding, oven, autoclave, etc.) in a restricted mold to keep the required shape, the wax is removed at low heat by drilling a hole or removing the ends. The result is very high strength RP product. Its shape can be rectangular, round, curved, etc. This process was used during 1944 to fabricate the first all plastic airplane using the bag molding process fabricating principally RP sandwich monocoque construction.[1, 424]

Spray-Up

This process has been a popular system with RP production for over half century. With time passing, significant new developments occur particularly in the spraying equipment. An air spray gun includes a roller cutter that chops usually glass fiber rovings to a controlled short length before being blown in a random pattern onto a surface of the mold. This action can be manual or automatic. Suppliers of spray-up equipment continue to produce cleaner, reduced styrene emissions (as low as 2.2%), higher capacity, more uniform spray pattern, and more versatile.[295, 442] Types and performances of spray guns are many such as external or internal mixing gun, distributive/turbulent mixing gun, air atomized, airless, etc.

As the fibers leave the spray gun simultaneously the gun sprays the usual catalyzed TS polyester plastic (with styrene monomer, Chapter 2). The chopped fibers are plastic coated as they exit the gun's nozzle. The resulting, rather fluffy, RP mass is consolidated with serrated rollers to squeeze out air and reduce or eliminate voids. A closed mold with appropriate temperature and pressure produce products.

Stamping

Reinforced thermoset (RTS) plastic B-stage sheet material can be processed with its required heating cycle. However the most popular is to use reinforced thermoplastic (RTP) sheets usually using polypropylene plastics. Compared to injection molding RTPs, these stamped products can provide improved mechanical and physical properties with its longer fibers such as impact strength, heat distortion temperature, and much less anisotropy.

The reinforced plastic sheet material is precut to the required size depending on the part size to be molded. The precut sheet is preheated in an oven, the heat required depends on the TP used [such as PP or nylon, where the heat can range upward from 270 to 315C (520 to 600F)]. Dielectric heat is usually used to ensure that the heat is quick and, most important, provides a uniform heating through the thickness and across the sheet. After heating, the sheet is quickly formed into the desired shape in cooler matched-metal dies, using conventional metal stamping presses or SMC-type compression presses.

Stamping is potentially a highly productive process capable of forming complex shapes with the retention of the fiber orientation in particular locations as required. The process can be adapted to a wide variety of configurations, from small components to large box-shaped housings and from flat panels to thick heavily ribbed parts.

Cold Forming

This process is similar to the hot-forming stamping process. It is a process of changing the shape of a plastic sheet or billet in the solid phase through plastic (permanent) deformation with the use of pressure dies. The deformation usually occurs with the material at room temperature. However, it also includes forming at a higher temperature or warm forming, but much below the plastic melt temperature, and lower than those used in thermoforming or hot stamping.

Different forms of glass fiber-TS plastics are used with or without special surface coatings such as gel coatings. Materials are compounded with controlled pot life so that they start their cure reaction after being placed in the mold cavity. For room temperature cure, cure occurs by an exothermic chemical reaction that heats the RP. Pressures are moderate at about 140 to 350 kPa (20 to 50 psi). Molds can be made of inexpensive metal, plaster, RP, wood, etc.

Comoform Cold Molding

This is another version of cold forming by utilizing a thermoformed plastic skin to impart an excellent surface and other characteristics (for weather resistance, etc.) to a cold-molded RP. For example, a TP sheet is placed in a matched mold cavity with an RP uncured material placed against the sheet. The mold is closed and the fast, room temperature curing plastic system hardens. The finished product has a smooth TP-formed sheet backed-up with RP.

Selecting process

The different processes available for fabricating RPs each tend to have their own specific performance and cost capabilities. It is important to recognize that the process can have a significant effect on the performance of the finished product. When more than one process exists, the process to be used may involve studying the repeat output quality available of each process to meet requirements using the least amount of plastic and reinforcement. The choice can be related to the type of plastic to be processed, pressure/temperature curing requirements, quantity of products, size of product, production rate, tolerances required, etc. Each process, like each material of construction has their capabilities or limits. The following Tables 15.8 to 15.9 provide information on different processes with properties and characteristics of RPs.

Table 15.8 Examples of interrelating product-RP material-process performances

Design parameter	Resin-transfer molding	Spray-up	Hand lay-up	Sheet molding compound
Minimum inside radius, in. (mm)	$\frac{1}{4}$ (6.35)	$\frac{1}{4}$ (6.35)	$\frac{1}{4}$ (6.35)	$\frac{1}{16}$ (1.59)
Molded-in holes	No	Large	Large	Yes
In-mold trimming	No	No	No	Yes
Core pull and slides	Difficult	Difficult	Difficult	Yes
Undercuts	Difficult	Difficult	Difficult	Yes
Minimum recommended draft (deg.)	2 to 3	0	0	1 to 3; 3, or as
Minimum practical thickness, in. (mm)	0.080 (2.0)	0.060 (1.5)	0.060 (1.5)	0.050 (1.3)
Maximum practical thickness, in. (mm)	0.500 (12.7)	No limit	No limit	1 (25.4)
Normal thickness variation, in. (mm)	±0.010 (±0.25)	±0.020 (±0.50)	±0.020 (±0.50)	±0.005 (±0.1)
Maximum thickness buildup, heavy buildup (ratio)	2 : 1	Any	Any	Any
Corrugated sections	Yes	Yes	Yes	Yes
Metal inserts	Yes	Yes	Yes	Yes
Bosses	Difficult	Yes	Yes	Yes
Ribs	Difficult	No	No	Yes
Hat section	Yes	Yes	Yes	No
Raised numbers	Yes	Yes	Yes	Yes
Finished surfaces	2	1	1	2

Problems that exist when evaluating processes can take into consideration factors such as insufficient compaction and consolidation before plastic solidification or cure occurs before air pockets develop, incomplete or uncontrollable wet-out and encapsulation of the fibers, and/or insufficient fiber or uniform fiber content. These deficiencies lead to loss of strength and stiffness and susceptibility to deterioration by water and aggressive agents. Heat control may not be adequate particularly for crystalline plastics or it may be too rapid (Chapter 1).

Table 15.9 Guide to product design shapes vs. processing methods

Part design	Casting	Compression	Filament winding	Injection	Matched die molding	Rotational	Transfer compression	Wet lay-up (contact molding)
Major shape characteristics	Simple configurations	Moldable in one plane	Structure with surfaces of revolution	Few limitations	Moldable in one plane	Hollow bodies	Simple configurations	Moldable in one plane
Limiting size factor	Material	Equipment	Equipment	Equipment	Equipment	Material	Equipment	Mold size
Minimum inside radius, in. (mm)	0.01–0.125 (0.25–3.18)	0.125 (3.18)	0.125 (3.18)	0.01–0.125 (0.25–3.18)	0.06 (1.5)	0.01–0.125 (0.25–3.18)	0.01–0.125 (0.25–3.18)	0.25 (6.4)
Minimum draft (deg.)	0–1	>1	2–3	<1	1	1	1	0
Minimum thickness, in. (mm)	0.01–0.125 (0.25–3.18)	0.01–0.125 (0.25–3.18)	0.015 (0.38)	0.005 (0.1)	0.03 (0.8)	0.02 (0.5)	0.01–0.125 (0.25–3.18)	0.06 (1.5)
Threads	Yes	Yes	No	Yes	No	Yes	Yes	No
Undercuts	Yes[1]	NR[2]	NR	Yes[1]	NR	Yes	NR	Yes
Inserts	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Built-in cores	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes
Molded-in holes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Bosses	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes
Fins or ribs	Yes	Yes	No	Yes	No[6]	Yes	Yes	Yes
Molded-in designs and nos.	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes
Overall dimensional tolerance (in./in., plus or minus)	0.001	0.001	0.005	0.001	0.005	0.01	0.001	0.02

In some applications the design or fabricator will not have the ability to choose freely from all the design, material, and process alternatives. For example, a design is often heavily constrained by the need to fit an existing assembly and the material and process may be determined largely by the need to use existing fabricating facilities.

The geometric symmetry of a product can influence process selection. Both shape and design details are heavily process related. The ability to mold ribs, for example, may depend on material flow during a process or on the flowability of a plastic reinforced with glass. The ability to produce hollow shapes depends on the ability to use removable cores, including air, fusible or soluble solids, and even sand. Hollow shapes can also be produced using cores that remain in the product, such as foam inserts in RTM or metal inserts in IM.

A process's pressure and the available equipment can limit product size, whereas the ability to achieve specific shape and design detail is dependent on the way the process operates. Generally, the lower the processing pressure, the larger the product that can be produced. With most labor-intensive methods, such as hand lay-up, slow-reacting TSs can be used and there is virtually no limit on size.

There may be a requirement for surface finish, molded-in color, textured surface, or other conditions the plastic material is to meet (Chapter 2). The different processes may be able to provide only one surface to be smooth or both sides are smooth. Important that smooth be identified since it has many meanings to different people. Surface finish can be more than just a cosmetic standard. It can also affect product quality, mold cost, and delivery time. The Society of Plastics Engineers/Society of Plastics Industries standards range from a No. 1 mirror finish to a No. 6 grit blast finish. A mold finish comparison kit consisting of six hardened tool steel pieces and associated molded pieces is available through SPE/SPI.

Tolerance

The thermoset (TS) plastics and reinforced thermosets (RTSs) are more suitable to meet tight tolerances. With amorphous and crystalline thermoplastics (Chapter 1) reinforced thermoplastics (RTPs), and particularly unreinforced thermoplastics (UTPs) can be more complicated tolerance-wise if the fabricator does not understand their behavior. Crystalline plastics generally have different rates of shrinkage in the longitudinal (melt flow direction) and transverse directions when injection molded.

Shrinkage changes can occur at different rates in different directions. These directional shrinkages can vary significantly due to changes in processes such as during injection molding (IM) (Chapter 4). Activity is influenced by factors such as injection pressure, melt heat, mold heat, and part thickness as well as shape. The amorphous type melt flow can be easier to balance.

Shrinkage is caused by a volumetric change in a material, particularly RTP, as it cools from a molten to a solid form. Shrinkage is not a single event since it can occur over a period of time for certain plastics, particularly TPs. Most of it happens in the mold, but it can continue for up to 24 to 48 hr after molding. This so-called post-mold shrinkage is when a product might be constrained in a cooling fixture. Additional shrinkage can occur principally with RTPs when annealing or exposure to high service temperatures relieves frozen-in stress.

The main considerations in mold design effecting product shrinkage are to provide, for instance, with IM of RTPs, adequate cooling, proper gate size and location, and structural rigidity. Of these three, cooling conditions is the most critical, especially for crystalline TPs.

Certain plastics, such as TS polyester during crosslinking (curing), generate heat that is controlled by constituents such as their styrene content; this, in turn, influences shrinkage (Chapter 1). In small batches, heat is generated in a controlled manner. In larger batches, the heat generated can cause discoloration or cracking. Modifiers can be added to lower the cross-linking rate. The formation of the crosslinked network is accompanied by some volume contraction. TSs with high styrene content crack as a more rigid structure attempts to shrink. Fillers, inorganic extenders, and fibers reduce the shrinkage and also can eliminate internal voids and cracking.

A number of the computer-aided flow simulation programs offer modules designed to forecast product shrinkage (and, to a limited degree, warpage) from the interplay of plastic and mold temperatures, cavity pressures, molded part stress, and other variables in mold-fill analysis. The predicted shrinkage values in various areas of the product should be used as the basis for sizing the mold cavity, either by manual input or feed-through to a mold-dimensioning program. All the programs can successfully predict a certain amount of shrinkage.

To meet tolerances or shrinkages (as with other materials), more is needed to be applied than simple arithmetic. An important requirement is that someone such as the product moldmaker be familiar with plastics behavior and, particularly, its fabrication method. Of course, with experience in a product equal or similar, as with other materials, setting tolerances and shrinkages is automatic.

Tolerances should not be specified tighter than necessary for economical production. However, after production starts, the target is to mold as 'tight' as possible to be more profitable by using less material and/or reducing molding cycle time which result in lower fabrication cost. There are unreinforced molded plastics that change dimensions (shrink) immediately after or in a day or a month due to material relaxation and changes in temperature, humidity, and/or load application. RPs can significantly reduce or even eliminate this dimensional change after molding.

Using any calculated shrinkage approach provides a guide in simple shapes. For other shapes, some critical key dimensions of the product will, more often than not, not be as predictable from the shrink allowance, particularly if the product is long, complex, or tightly toleranced. This situation also exists with other materials (steel, aluminum, etc.). Determining shrinkage involves more than just applying the appropriate correction factor from a material's data sheet. Data sheets provide guides.

16 OTHER PROCESSES

Introduction

When analyzing processes to produce all types of products, at least 65wt% of all plastics require some type of specialized compounding. They principally go through compounding extruders, usually twin-screw extruders, before going through equipment such as injection molding machines, extruders, and blow molding machines to produce products.[303–306]

As reviewed in Chapter 3 many different processes are used. What has continually been happening for over a century in the plastic industry worldwide is that many designers, researchers, engineers, chemists, fabricators, material suppliers, equipment suppliers, and others have been able to manipulate the basic temperature, pressure, and time fabricating plastic cycle to their advantage by minor or major changes to the popular processes. As an example, new materials that are developed may need certain processing techniques requiring modifications of the more popular processes.

Many of these processes overlap as to how they operate and most meet specific needs to produce a specific product. Unfortunately many of these new processes follow the art of reinventing the wheel such as adding a decorative surface that is important but not earth shattering. An example of overlapping is the so-called reinforcing plastic (RP) processes. When this part of the plastic industry developed over a half century ago TS polyester-glass fiber RPs were bag molded, autoclaved, filament wound, and so on (Chapter 15). They expanded in using other materials, reinforcements, and processes that include all the major processes and a few more. As an example we have had the process of reinforced injection molding; in fact over 50% of all RPs go through these machines.

Out of this experience come new processes such as in the past there was transfer compression molding and more recently came reaction injection molding (RIM). Very important is the fact that this development action continues to advance the use of the basic processes used in the industry. Those basic processes and a few others have been reviewed in this book. In this chapter a few of the others are reviewed.

PVC dispersion

The vinyl dispersion industry provides many different products worldwide and uses different processes. When reviewing vinyl dispersions there are basically two types known as plastisol and organosols. These dispersions and examples of processes used will be reviewed.

Plastisol

The main type used is the plastisols that contains no volatile thinners or diluents. Plastisols can be made into thick fused sections with no concern for solvent or water blistering, as with solution or latex systems, so they are described as being 100% solids materials. With the application of heat to plastisol they can be processed by different methods to produce flexible to hard parts. Processes include casting, coating, dipping, spray, rotational molding, and continuous coating. Plastisol is a liquid suspension of a finely divided plastic (about 1μm) in a plasticizer. With heat, the plasticizer is absorbed into the particles and solvates them so that they fuse together to produce a homogeneous plastic mass. Fabricated parts are many. They include toys, beach balls, squeeze syringes, gloves, and interior parts for transportation vehicles.[98, 99, 307, 308]

When the plastisol is heated, it passes through several characteristic changes. As the PVC approaches its glass transition temperature, the plasticizer begins to swell the PVC particles. The plastisol gels when the PVC has absorbed all the plasticizer at a temperature about that of the PVC glass transition temperature (T_g) (Chapter 1). At this stage it is dry and shattered, without cohesive strength. Fusion and the development of physical properties begin when the plastisol temperature reaches approximately 120C (280F). By the time the plastisol temperature is approximately 190C (380F), the plastisol is fully fused but still liquid. Fusion is technically defined as the condition where the microcrystallites of PVC have fully melted and the plasticizer is fully dispersed through the PVC. When heated the plasticizer is absorbed into the particles and solvates them so they fuse together to produce a homogeneous mass. The fusion process is called gelation.

To meet specific needs, other additives such as lubricants, extenders, fillers, impact modifiers, and pigments are added to the PVC compound, in addition to heat stabilizers and plasticizers. Today, it is estimated that more than 60% of all the adducts used in plastics are used in PVC compounds. Although the earliest PVC compounds were produced as emulsions, essentially all PVC compounds are produced today as suspensions. Suspension compounds contain essentially no emulsifiers and are more processable. Liquid plastisols typically have room-temperature viscosities of less than 10,000 cp. Products made from plastisols are usually very soft. They have Shore Durometers of 55A and less, to as low as 30A, and they can have characteristic skin- or leather-like appearance and feel.

When these 100% solid plastisols are formed there is a slight shrinkage or increase in density. A small amount of shrinkage occurs because the vinyl compound usually shrinks more on cooling than occurs with the mold material. This shrinkage is usually about 2%. The higher shrinkage values are with the softer plastisols.

Vinyl, typical of plastics, being a good insulator transmits heat slowly. The thickness of the finished product is determined by the amount of heat transmitted through the vinyl dispersion. Preheating temperatures tend to be high for thin molds and lower for thick molds. Finished product thickness is also influenced by the length of time the plastisol is in or around a mold. As an example with dip molding (around a mold) the mold should typically be withdrawn from the plastisol slowly and smoothly, otherwise lines will form on the product. With excessive draining, there will be runs and streaks on the product. The mold should contain sufficient residual heat and should be withdrawn slow enough that the fluid plastisol runs off and the remainder gels immediately without running or dripping. When this cannot be accomplished, it may be possible to rack the products so that runs drip from one corner; then, by inverting the products, the last drip can flow back.

Many different processing methods are used, all with the essential element of heat. These processes permit products to be made that would otherwise require costly and heavy melt processing complicated molds and/or equipment. Different types of dispensing equipment are used to meet different flow rates and delivery amounts. No pressure or mixing is necessary. This means that mold costs are very low and the overall processing equipment costs are low. They are very versatile materials in that almost any additive can be incorporated for special effects as long as it is soluble in the plasticizer or can be ground to a powder sufficiently fine to be suspended in the plastisol.

During processing, the plastisol is heated slowly. When the gel point is reached, the plastic absorbs the plasticizer. However, in a very soft compound, the plastic dissolves into the plasticizer. Because each plastic particle remains a separate particle, the resultant gel has no useful physical properties. But on further heating, the plasticized plastic partially melts and flows into the plasticizer; this occurs at the fusion point or over the fusion range. On cooling, the material comprises the tough rubber compound known as a flexible vinyl.

Viscosity of the plastisol changes as the temperature is raised starting at a low viscosity, increasing over the gel range, and peaking at the onset of fusion. The viscosity goes down during fusion. Satisfactory processing of vinyl plastisols requires an understanding of gelation and fusion, their mechanisms and their effects on molding and cooling. Because the vinyl is a relatively good insulator, it takes time for the heat to penetrate completely.

The ovens used for processing vinyl dispersions may be gas-fired, electric, or infrared. They are required to provide uniform heat and provide sufficient exhaust to vent the smoke produced by the hot plastisol through a suitable ventilating system exposing clean air into the atmosphere.

Organosol

Organosols are similar to plastisols except that part of the plasticizer is replaced with a solvent. Plasticizers are dissolved in the volatile liquid. They are suspensions of finely divided plastic in a volatile organic liquid. Using solvent makes them less expensive. In the past there were fabricators that discharged the solvent into the atmosphere. Organosols now must use safe ventilation systems.

Organosol production is more cost-effective with a solvent recovery system. The vinyl does not dissolve appreciably in the organic liquid at room temperature. It dissolves at elevated temperature. The liquid solvent evaporates at the elevated temperature. The residue remaining upon cooling is a homogeneous plastic mass.

In some specially developed organosol coating systems, it has been practically impossible to design solvent systems which would produce good flow, aid in proper fuse-out of the film, and still be viscosity-stable on storage. Such coating materials are sold as two-package systems. The organosol component contains a balanced solvent system for the ingredients contained therein, yielding a storage-stable liquid that may be clear or pigmented. The catalyst component, which may contain the modifying plastics or crosslinking agents also utilizes solvents that are properly balanced for this component and it forms a storage-stable liquid, clear or pigmented.

Slush Molding

Slush molding produces hollow products from vinyl plastisols. It is the reverse of plastisol dip molding and an offshoot of open molding. Slush molding has been extensively used for making dolls, balls, flexible toys of all sorts; fishing hip-boats, automobile parts (gearshift boots, armrests, headrests, etc.), road-safety cones, and others.

The mold may be split or one-piece. The finished part is removed either by splitting the mold or, in the case of a one-piece mold, by collapsing the part with a vacuum. This process can be very labor intense. However it is also automated requiring relatively no labor. Automatic systems fill molds with plastisol carried by conveyor belts through an oven as it is being slushed (the mold is put into a control motion pattern). The plastisol can gel repeatedly to a thickness of 0.06 in. (15.2 mm). The excess plastisol is poured out of the mold and automatically returned to the main tank for reprocessing. The molds proceed to another oven where curing is completed.

The process is temperature-time dependent. It goes through the following stages:

(a) mold with a female cavity is preheated,

(b) mold cavity is filled with a measured amount of plastisol,

(c) preheat sufficiently to gel the required thickness of plastisol; mold is filled and held for several seconds before it is inverted and drained,

(d) plastisol in the heated mold is dispersed (slushed) evenly over the inner cavity surface by back-and-forth motion of the mold, side-to-side motion, and/or rotation, usually around one axis,

(e) heated mold causes gel to occur,

(f) drain excess plastisol out of the mold,

(g) applied heat fuses the plastisol,

(h) cool, via water, the mold that cools the vinyl

(i) remove the flexible product from the mold and trim if required.

By filling a cold mold followed with heat produces a gel or a skin on the mold cavity. This procedure can improve the reproducibility of the mold texture or engraving on the cavity wall. Care is required when using a cold-mold approach because the plastisol can gel on the air entrapped in the cavity or the outside surface producing poor drainage and forming lumps in the plastisol. The lumps can cause the product to have uneven thickness and/or performance. The lumps have to be screened out of the remaining plastisol that is recycled on the following slush moldings, causing further problems.

Rotational Molding

Rotational molding of vinyl plastisols is similar to the rotational molding of powder or liquid plastics (Chapter 13). Plastisol is placed in the mold and heated while the mold is being rotated. Molded products can include tanks, volleyballs, basketballs, doll heads and bodies, and various automobile parts.

Spray Molding

Plastisols being in liquid form can be sprayed on molds or parts (Chapters 7, 8, 10, and 15). Thicknesses of up to 50 mil (1.3 mm) can be obtained in a single pass on a vertical panel. The sprayed parts are heated and cooled. Multiple passes are made to increase the thickness. After cooling they are stripped off the mold or left on as a coating. Popular is the spraying of plastisols or organosols liners in small to very large tanks. With organosols it is possible to spray a thicker or harder film coating than is feasible with plastisols. Such coating films are used to replace paint films in applications where the chemical resistance of vinyl is required.

Continuous Coating

This procedure identifies plastisols that are spread-coated on different substrates such as paper, aluminum foil, wood, and plastic sheet or film. Application is by doctor blade, direct roll, or reverse roll operations (Chapter 10). As an example plastisols are roll coated on adhesively primed metal for house sidings, conveyor belts, cloth fabrics, wood panels, and so on.

There are also other products produced such as foamed vinyl fabrics (Chapter 8). One method of fabrication is to coat a thin layer of solid plastisol on embossed release paper, then coating a thicker coating of foam plastisol and finally layering on a cloth scrim. The composite is fused and peeled from release paper. The wear layer of vinyl flooring is usually a coated clear plastisol, making it a no-wax flooring.

Principal vinyl resins used in coatings are the copolymers of vinyl chloride and vinyl acetate. Polyvinylidene chloride (PVDC) and polyvinyl butyral (PVB) are also important. Polyvinyl acetate (PVAc) in emulsion form is widely used in architectural coatings. The vinyl copolymers produce air-drying coatings that have excellent toughness and good resistance to water and chemicals. However, they are sensitive to heat, ultraviolet radiation, and many solvents. They are high polymers and therefore require fairly strong solvents. Development of the dispersion type of vinyl resin permits their application as organosols and plastisols at high solid content, which extend their usefulness considerably. They do not have high solids at spraying consistency.

Vinyl resins are widely used as fabric coatings because of their combination of toughness and flexibility, and their property of not supporting combustion. Because they are nonflammable they replaced nitrocellulose lacquers for many applications on fabrics. They produce excellent coatings on metals but care must be taken in their application because, like most high polymers, they have strong cohesive forces that may overcome the adhesive forces. The entire coating may flake off as a continuous sheet if the precise application conditions have not been complied with for the various modifications.

The absence of odor, taste, and toxicity in vinyl coatings makes them suitable for the lining of beer cans. They have other applications in food containers but certain limitations exist. Namely, poor adhesion and sensitive to temperatures used in processing foods.

The vinyl copolymers can be used most efficiently in special applications such as hospital and dental equipment where durability is more important than initial cost. For laboratory equipment, epoxy resins may be preferred because the vinyls are sensitive to some solvents. The vinyl coating systems consisting of corrosion-inhibiting primer and chemical-resistant finish coats are used on new equipment for chemical plants. The metal conditioner based on zinc chromate and polyvinylbutyral are widely used over sandblasted steel as a use for vinyl systems on both industrial and marine equipment.

Polyvinyl acetate (PVAc) in the pure and solid form is colorless and transparent. It is somewhat brittle unless the degree of polymerization is low. Its softening temperature is between 40 and 90F (4 and 32C), depending on the molecular weight. It shows the phenomenon of cold flow.

Polyvinyl alcohol (PVAL) because of its water solubility has a relatively small part to play as a binder in surface coatings. It has been used as an impregnant in the production of greaseproof paper, as a yarn sizing and for the production of water-soluble packages. It is useful as a dispersing agent and protective colloid, for example in latex paints. It has the advantage over glue and casein that it is much less susceptible to microbiological attack.

Nonfoam Strippable Vinyl

Another group of chemical coating, the use of which have shown continued mark expansion are the nonfoam strippable vinyls. While these materials have been offered for some time, they were formulated for spray application to products after fabrication. The more recent types, like the roll-coat finishes, are designed for application by reverse roller coating to coiled metal before the product is manufactured (Chapter 10). Therefore they offer surface protection all the way through metalworking operations, during assembly, and many times afterward as preliminary packaging.

These types generally consist of vinyl plastisols, applied in liquid form and heat-converted into a continuous film, generally at a minimum of about 2 mils dry. Here again, improved resins have played an important part in the superior performance of these materials by providing them with excellent toughness as well as tensile and tear strength to withstand slitting, stamping, forming and bending.

Formulated with just the right degree of cohesive properties to adhere until no longer desired, these strippables can be used over a variety of substrates including polished or stainless steel; anodized aluminum; or prefinished metal that has been coated with thermoset finishes.

There are different applications of plastisol strippable vinyl in which the users reduced its material and labor costs 50% by adopting this concept. There is the strippable on anodized aluminum coil that is subsequently manufactured into products such as heating hoods. For this application the strippable remains intact before, during and after fabrication; acts as preliminary packaging and protection against scratching from the ultimate corrugated container; and stays on until the hood is installed to protect it from installation handling.

Prior to using the plastisol strippable, companies employed pressure sensitive paper. This material was almost twice the cost per square foot and had to be removed before the hood was shipped; thus additional packaging had to be used.

Another example of strippable plastisol coatings is in the architectural field on stainless steel building panels. Here they offer surface protection from, before and during the panels' fabrication, until after they are erected.

Foam-Vinyl Strippable

The foam-vinyl strippables are very useful for packaging products such as metal parts. Based on polyvinyl chloride dispersion resins, they are applied in liquid form to the completed product. Foaming takes place during their cure cycle to produce a highly resilient, spongy film. Therefore these strippables also offer protection against denting, as well as scratching, and have taken the place of paper and corrugated wrappings at substantial savings.

Within the past few decades, types have been made available that can expand up to 300%. These can yield maximum films of about a ½ in., although a ¼ in. is more commonly used. Spraying, dipping, flow and curtain coating can apply foam-vinyl strippables, over the same substrates as the nonfoam types. Example of a major use is on chrome-plated automotive replacement parts, such as bumpers, headlight bezels, and decorative trim. Use of foam vinyl strippable protective coatings boosts production of wrapped parts considerably, besides lowering its reject rate. Output of wrapped bumpers, for example, was increased three times.

These materials afford many other advantages. For instance, they retard corrosion by forming a tight skin around the object, which inhibits the entrance of moisture. They also help to save space since this tight fit allows more units to be stacked per cubic foot than if bulky containers were used. In addition, because one type of strippable can accommodate all sizes and shapes, there is no need to maintain a large inventory of different sized packaging materials. While auto parts packaging is one of their larger uses, foam vinyl strippables are also used in other industries in which metal parts shipment prevails.

Open Molding

Most of the plastisols are used in open molding. It is a very simple process to use. A measured amount of plastisol is poured into an open mold cavity. The mold and plastic are heated to gel and fuse the plastisol. The mold is then cooled so that it solidifies. It is stripped from the mold. Inserts can be placed in the liquid plastic before it is fused; inserts can also be inserted in the mold before pouring. Two or more colors can be placed in different parts of the mold.

This process is used to produce all kinds of commercial and industrial products. Examples include automotive air filters, tablecloths, coin mats, truck flaps, simulated fishing worms, other baits, display items, various novelties may be encased, and many other relatively flat to complex shaped products.

Special applications with special compounding include a major market for automotive oil filters where additives are included in the compound; the additive causes the plastisol to bond to the filter media and to the metal endcap. The plastisol then becomes both an adhesive and an end seal for the oil filter. Table 16.1 provides an example of a PVC formulation.

Table 16.1 Example of a PVC blend formulation

Ingredient	Common Type	Concentration (parts/hundred)
PVC suspension resin	Homopolymer, 0.68–0.74 IV	100.0
Tin stabilizer	Mercaptide, 13–20% tin	1.2–2.0
Processing aid	Methacrylate copolymer	1.5–3.0
Costabilizer/lubricant	Calcium stearate	0.5–2.0
Filler	Calcium carbonate, 1–3 μm	0–5
Pigment/UV stabilizer	Titanium dioxide	1–2
Impact modifier	ABS or MBS polymer	0–5
Lubricant	Paraffin wax or fatty acid amide or fatty acid esters	0.5–1.5

Closed Molding

This process resembles the open molding process except it is closed like a two-part compression mold (Chapter 14). A measured amount of plastisol is poured or pumped into the closed mold cavity, similar to close molding except that a slight pressure of about 5 psi (34.5 kPa) is applied. The mold is heated to fuse the plastisol then cooled. Later the mold is opened and the product stripped out. This process can provide for accurate thickness control, filling very complex shaped parts, and so on.

Dip Molding

Dip molding is similar to of dip coating. With dip molding the solidified plastisol is stripped off the mandrel or mold. In dip coating the vinyl and mandrel or mold becomes part of the finished product (Chapter 10). The process for dip molding goes through the following stages:

(a) metal mold is preheated in an oven,

(b) mold is dipped in a tank of plastisol for a specified period of time based on the vinyl composition,

(c) removing the coated mold from the tank,

(d) allowing any excess plastisol to drain off the coated mold,

(e) placing the mold in an oven and heating until the plastisol and the mold reach the usual required temperature of 350F (177C),

(f) upon vinyl solidification removing from the oven and cooling the coated mold to 130 to 140F (54 to 60C),

(g) cooling can be done by hanging in cool air, by water spray, by actual dipping into water, or by their combinations

(h) stripping the plastisol off the mandrel or mold while it is still soft enough to stretch and pull over undercuts but cool enough not to be distorted by stretching.

Dip Coating

Chapter 10 provides information on coating different types of plastics by different fabricating processes. This section pertains specifically to dip coating with plastisols. Processing for dip coating is the same as dip molding except that the mold is part of the finished product. Plastisols do not adhere to metals or other mold materials. A primer adhesive is used if the coating requires adhesion. Primer adhesives are usually solvent-based or water-based adhesive lacquers that may be dipped, sprayed, or brushed on the metal part prior to being preheated and dipped in the plastisol tank.

Dip molding products are many that include short or long production runs. They include slip-on grips, medical gloves and certain instruments, automotive bumper guards and gear shift boots (accordion and/or straight boots), electrical devices (transformer and car battery leads, bus-bar insulation tubes, electronic controls, etc.), coating tool handles to insulate against heat and cold, insulating field coils for car starters, cushioning kitchen tools, electrically insulating all kinds of devices that perform in hot or cold environments, and providing protective coverings for sharp tools.

Ink Screening

Ink screening was previously called silk screening. It is very popular in applying highly pigmented colored plastisols on T-shirts, sportswear, etc. The ink becomes heat-fused.

Encapsulation

Encapsulation can also be called embedding. This process encloses products in plastic. These products are very diversified. They include ornaments, solenoids, medical devices, sensors, motor components, and integrated circuits. Different processes can be used to encase products that range from casting (Chapter 11) to injection molding (Chapter 4). This is a simple process, similar to the review for casting. It is suitable for high volume and automation at a very low cost. Inserts of any size, shape, and number can be encapsulated. Either thermoplastics or thermoset plastics can be used with or without reinforcements such as milled glass fibers to meet different performance requirements.

To insert a product it can be just immersed in a plastic liquid prior to the plastic hardening. The product could have fixed spider type supports or retractable pins or other features to support it when molten plastic is poured or injected around it. Another approach is to place the product on a layer of plastic that is partially polymerized in a mold cavity followed by applying a final layer that physically encloses it. For certain plastics and/or products a vacuum system can be used if air pockets or voids are to be eliminated.

Potting

Potting involves casting a plastic in a shell that is a container representing a mold cavity. Within the plastic a product could be embedded. Potting is similar to encapsulation except that the shell is not separated from the finished product. It is an embedding technique in which the shell and plastic remains consolidated.

Liquid injection molding

Liquid injection molding (LIM) is a variation of the reaction injection molding (RIM) process (Chapter 11).

It is different to reaction injection molding (RIM) where it uses a mechanical mixing rather than a high-pressure impingement mixer (Figures. 11.1 and 11.2). The entire shot is mixed in a chamber before injection into the mold, rather than being continuously mixed and injected, as in the RIM process. LIM is used to mold smaller parts that are below the desired capacity of RIM. LIM also allows higher-viscosity materials to be processed.

LIM offers an automated low-pressure processing of (usually) conventional liquid TPs or TSs and RPs having faster molding cycles, low labor cost, low capital investment, energy saving, and space saving.

Because the pressures of injection are low at approximately 25 to 50 psi (172 to 345 kPa) very fragile inserts can be molded and mold wear is at a minimum. Some formulations for LIM also may be molded at temperatures as low as 200F (93C) which permit the encapsulation of some heat-sensitive electronic components that do not lend themselves to encapsulation at conventional transfer molding temperatures of 300F (149C) or higher.

Vacuum Assisted LIM

The vacuum assisted liquid molding process has been used for the manufacture of large composite parts. In this process, a preform is placed in an open mold and a plastic vacuum bag placed on top of the mold. A vacuum is created in the mold using a vacuum pump. A resin source is connected to the mold. As vacuum is drawn through the mold, resin infuses into the preform. Application includes the fabrication of large products with complex geometry such as panels of all-composite buses, railroad cars, and vehicle components.

Impregnation

This method has been popular impregnating liquid plastic in products such as electrical coils and transformers. The liquid plastic is forced by pressure, vacuum, or their combination into the interstices of the component. A related process is *trickle impregnation.* It uses reactive (polymerizable) plastics with a low viscosity, first catalyzing them followed with dripping them onto a transformer coil or similar device with small openings (Chapter 1). Capillary action draws the liquid into the openings at a rate slow enough to allow escape of the air displaced by the liquid. When the device is fully impregnated exposing it to heat cures the plastic system.

Chemical etching

This is the exposure of certain plastic surfaces to a solution of reactive chemical compounds. Solutions are oxidizing chemicals, such as sulfuric and chromic acids, or metallic sodium in naphthalene and tetrahydydrofuran solutions. Such solutions are highly corrosive; thus, require special handling and disposal procedures. This treatment causes a chemical surface change, such as oxidation, thereby improving surface wettability, increasing its critical surface tension. It may also remove some material, introducing a micro-roughness to the surface.

Chemical etching requires immersion of the part into a bath for a period of time, then rinsing and drying. This process is more expensive than most other surface treatments, such as flame treatment, thus it is used when other methods are not sufficiently effective. Fluoroplastics are often etched chemically because they do not respond to other treatments, ABS are usually etched for metallic plating, and so on.

Twin screw injection molding extruder

Glass fiber reinforcements are added to plastics in order to improve mechanical and physical properties of the plastic. The traditional route to producing fiber reinforcement involves blending the fibers into plastic in a twin-screw extruder followed by pelletization (Chapter 5). The pellets are then molded using an injection molding machine (IMM) to form the fabricated products (Chapter 4). This action results in fiber attrition.

The twin-screw injection molding extruder is an injection molding machine that is capable of both blending/compounding and extrusion in one step. Because it is a one step process, the fibers never go through the entire extrusion process as well as the pelletization that limits the fiber size, but are blended into the molten plastic before injection. The screw part of this machine is based on a non-intermeshing, counter-rotating twin-screw extruder (Chapter 5). One of the screws in this machine is capable of axial movement and has a non-return valve on the end. This action enables the screw to inject and mold parts.

Melt compression molding

Melt compression molding identifies in-mold laminating and in-line molding of carriers, decorations, etc. The basic technique has been used for over a century. There has been an increased application of textile cover stock and leather substitutes both preferably with a soft touch. This type development was primarily initiated by the automotive industry with the objective to be prepared for future trends. Other industries such as furniture and packaging manufacturers use this process.

Different methods are used such as back injection including the injection-compression molding and melt flow compression molding.

Mold design is a decisive factor for the molding success such as dimensioning and location of the sprue gates, dimensioning of shear edges, flow aids, cooling and ejector techniques, etc.

With backpressure the process is performed in conventional injection molding machines (IMMs) (Chapter 4). The cover stock is inserted and located in an open mold. A shear edge mold permits draw-in of the cover stock during the closing cycle to avoid wrinkles and damage by stretching of the fabric. Molds require special attention. They generally use a hot runner system with its shut-off nozzle(s). All mold elements such as ejector, core pulls, and slides have to be on the injection side mold half.

Also used is the injection-compression cycle where after a preforming stroke for the cover stock, the carrier material is injected in a partially open mold (Chapter 4). By closing the gap the part is formed and laminated. The mold corresponds to a back injection mold. The method has similarities with melt flow compression molding.

Melt flow molding is performed on vertical clamping IMMs. The cover stock is inserted into an open mold followed with the mold partially closed. The carrier stock is injected from below through a hot runner system and several gates with actuated control needle shut-off nozzles. The final melt shot from the gates is compression formed into the part by closing the remaining mold gap. Shear edge molds with hot runner systems similar to those for back injection are used.

Back compression is a process based on compression molding (Chapter 14) of a melt strip deposited in an open mold. It describes the process during which a cover stock cutting is placed on a melt strip for simultaneous compression molding and lamination of parts. Melt strip deposition also includes fiber reinforced thermoplastic stock with subsequent compression molding of non-laminated structural parts.

17 MOLD AND DIE TOOLING

Overview

When processing plastics some type of tooling is usually required. Tools include molds, dies, mandrels, jigs, fixtures, punch dies, perforated forms, etc. The terms for tools are virtually synonymous in the sense that they have some type of female and/or negative cavity into or through which a molten plastic moves usually under heat and pressure or they are used in secondary operations such as cutting dies, stamping sheet dies, etc. These tools fabricate or shape products. In this chapter injection molds and extrusion dies are primarily reviewed because they represent over 95% of all tools made for the plastic industry. This chapter also includes information applicable to other molds and dies used in the other processes; some of the other chapters too provide information applicable to their tools.

Mold and die tools are used in processing many different materials with many of them having common assembly and operating parts (pre-engineered since the 1940s) with the target to have the tool's opening or cavity designed to form desired final shapes and sizes. They can comprise of many moving parts requiring high quality metals and precision machining.[309] As an example with certain processes to capitalize on advantages, molds may incorporate many cavities, adding further to its complexity. Most tools have to be handled very carefully and must be properly maintained to ensure their proper operation. They are generally very expensive and can be very sophisticated.[310–315]

Tools of all types can represent upward to one-third of the companies manufacturing investment.[282] Metals, specifically steels, are the most common materials of construction for the rigid parts of tools. Some mold and die tools cost more than the primary processing machinery with the most common approaching half the cost of the primary machine. About 5 to 15% of tool costs are for the material used in their manufacture, design about 5 to 10%, tool building hours about 50 to 70%, and profit at about 5 to 15%.

There are standards for materials of construction such as those from the American Iron and Steel Institute (AISI) and German Werkstoff. The proper choice of materials for their cavities (openings) is paramount to quality, performance, and longevity (number or length of products to be processed) of tools. Desirable properties are good machinability of component metal parts, material that will accept the desired finish (polished, etc.), ability with most molds or dies to transfer heat rapidly and evenly, capability of sustained production without constant maintenance, etc. (Table 17.1). As the technology of tool enhancements continues to evolve, tool manufacturers have increasingly turned to them to gain performance/cost advantages.

There are now a wide variety of enhancement methods and suppliers, each making their own claims on the benefits of their products. With so many suppliers offering so many products, the decision on which technology to try can be time consuming. There are toolmakers that do not have the resources to devote to a detailed study of all of these options. In many cases they treat tools with methods that have worked for them in the past, even though the current application may have different demands and newer methods have been developed. What can help is to determine what capabilities and features are needed such as hardness, corrosion resistance, lubricity, thermal conductivity, thermal expansion, polishing, coating, and repairing. This type of information is available on hard copies and software.[452, 483]

There are many tool metals such as D2 steel that are occasionally used in their natural state (soft) when their carbon content is 1.40 to 1.60wt%. Tool metals such as P20 are generally used in a pre-toughened state (not fully hardened).

By increasing hardness longer tool life can often be achieved. Increased wear properties are especially critical when fabricating with abrasive glass- and mineral-reinforced plastics. This is important in high-volume applications and high-wear surfaces such as mold gates inserts and die orifices. Some plastic materials release corrosive chemicals as a natural byproduct during fabrication. For example hydrochloric (HCI) acid is released during the tooling of PVC. These chemicals can cause pitting and erosion of untreated tools' surfaces. Also, untreated surfaces may rust and oxidize from water in the plastic and humidity and other contaminants in the air.

Table 17.1 Examples of the properties of different tool materials

AISI Designation Description	Hardness Rc	Hardening Temp (°F)	Tempering Temp (°F)	Heat Treatability	Compressive Strength	Corrosion Resistance	Wear Resistance	Toughness	Machinability	Polishability	Weldability	Thermal Conductivity
4140	30-36	1500	1200	10	4	1	2	8	6	5	4	5
P20	30-36	1600	1100	10	4	2	2	9	6	8	4	5
420SS	35-40	1865	1050	10	4	6	3	9	4	9	4	2
P5	59-61	1575	450	6	6	2	8	6	10	7	9	3
P6	58-60	1475	425	6	6	3	8	7	10	7	8	3
420SS	50-52	1885	480	8	8	7	6	6	7	10	6	2
440SS	56-58	1900	425	7	8	8	8	3	6	9	4	2
BECU	36-42	625	NR	7	2	6	1	1	10	9	7	9

Polishing and coating tools permit meeting product surface requirements. Improved release characteristics of fabricated products are a common advantage of tool coatings and surface treatments.[3] This can be critical in applications with long cores, low draft angles, or plastics that tend to stick on hot steel in hard-to-cool areas. Coatings developed to meet this need may contain PTFE (Chapter 2). Also used are metals such as chrome, tungsten, or electroless nickel that provide inherent lubricity.

Material of construction

Materials of construction can be of a simple design made from wood such as generally used in RP bag molding (Chapter 15). For the more sophisticated processes such as injection molding, extrusion, and blow molding (Chapters 4 to 6) it can comprise of many parts requiring high quality metals and precision metal machining.

The choices range from computer-generated tools that use specialty alloys or pure carbide tooling usually made from steels. Everyone from purchasing agents to shop personnel must consider the ramifications of tool performance requirements. One may consider the softest tool that will do the job because it is usually the least expensive to build but requires special/careful handling with limited life.

Different materials of construction principally use different grades of steels; others include types such as aluminum, beryllium copper alloy, brass, kirksite, sintered metal, steel powdered filled epoxy plastic, silicone, metal spray, porous metal, plaster of Paris, reinforced plastic, sand, wood, and flexible plastic. Commonly used is P20 steel, a high grade of forged tool steel relatively free of defects and it is available in a prehardened steel. It can be textured or polished to almost any desired finish and it is a tough mold material. H-13 is usually the next most popular mold steel used. Stainless steel, such as 420 SS, is the best choice for optimum polishing and corrosion resistance. Other steels and materials are also used to meet specific requirements in mold life and cost. The choice of steel is often limited by the available sizes of blocks or plates that are required for the large molds.[3, 163, 278, 299, 309, 317]

Some of the tool materials incorporate different special metals providing improvements in heat transfer, wear resistance of mating mold halves, etc. These special metals include beryllium copper alloy, brass, aluminum, kirksite, and sintered metal.

Manufacturing

Different conventional metal cutting methods are used to meet requirements based on type of material used and the configuration of the tool. As an example, the process of photochemical machining (PCM) is recognized by the metalworking industry as one of several effective methods for metal parts fabrication. The technique, also called photo-etching, chemical etching, and chemical blanking, competes with stamping, laser cutting, and electric-discharge machining (EDM). It uses chemicals, rather than mechanical or electrical power or heat, to cut and blank metal.

Photochemical machining has several distinct advantages over these other processes. Low tooling costs associated with the photographic process, quick turnaround times, and the intricacy of the designs that can be achieved by the process are some of the advantages, as are high productivity and the ability to manufacture burr-free and stress-free parts. Of paramount importance in using this process are the cost savings associated with generating prototypes.

The advantages of using fully hardening tool steels rather than case-hardening steels for the manufacture of tools, are primarily the simpler heat treatment and the possibility of making corrections to the cavity at a later time without a new heat treatment. However, the greater risk of cracking is a disadvantage, particularly for tools with a larger cavity depth, because tools from these steels do not have a tough core. Moreover, the tougher steels with a carbon content of about 0.4% do not attain the high surface hardness of about 60 HRC which is desirable with respect to wear and polish.

Sometimes the mechanical action of the tool may require certain steel selections so as to permit steel on steel sliding without galling. Tooling surfaces of precision optics will need steel that can be polished to a mirror finish. If the inserts will receive coatings to further enhance performance, then steel characteristics to receive coating or endure a coating process must be considered (coating application temperature vs. tempering temperature). Hot runner mold components often use hot work steel because of their superior properties at elevated temperatures. Very large molds and/or short run molds may use pre-hardened steel (270 to 350 Brinell) to eliminate the need for additional heat treatment.

When tool steels of high hardness are used they are supplied in the soft annealed condition (hardened mold inserts for cores, cavities, other molding surfaces and gibs, wedge locks, etc are typically hardened to a range of 48 to 62 RC. They are then rough machined, stress relieved, finish machined and go to heat treatment for hardening and tempering to desired hardness. After this heat treatment, the core or cavity typically must then be finish ground and/or polished. In some applications, there will be additional coatings or textures to further treat the tool surfaces.

When processing particularly highly abrasive plastics, the wear can still be too high even when using high-carbon, high-chromium steels. Metallurgical melting cannot produce steels with even higher amounts of carbides. In such cases hard material alloys, produced by powder metallurgy, are available as a tool material. These alloys contain about 33wt% of titanium carbide, which offers high wear resistance because of its very high hardness.

Like other tool steels, hard material alloys are supplied in the soft-annealed condition where they can be machined. After the subsequent heat treatment, which should if possible be carried out in vacuum-hardening furnaces, the hard materials attain a hardness of about 70 HRC. Because of the high carbide content dimensional changes after the heat treatment are only about half as great as those in steels produced by the metallurgical melting processes.

In machining as well as in non-cutting shaping processes stresses develop chiefly as a result of the solidification of surface layers near the edge. These stresses may already exceed the yield point of the respective material at room temperature and consequently lead to metallic plastic deformations. Since the yield point decreases with increasing temperature additional stresses can be relieved by plastic deformation during the subsequent heat treatment. In order to avoid unnecessary, expensive remachining it is advisable to eliminate these stresses by stress-relief annealing.

Electric-discharge machining (EDM), also called spark erosion, is a method involving electrical discharges between graphite or copper anode and a cathode of tool steel or other tooling material in a dielectric medium. The discharges are controlled in such a way that erosion of the workpiece takes place developing the required contours. The positively charged ions strike the cathode so that the temperature in the outermost layer of the steel rises so high as to cause the steel layer to melt or vaporize, forming tiny drops of molten metal that are flushed out as chippings into the dielectric.

EDM is a widely utilized method of producing cavity and core stock removal. Electrodes fabricated from materials that are electrically conductive are turned, milled, ground, and developed in a large variety of shapes, which duplicate the configuration of the stock to be removed. The electrode materials include graphite, copper, tungsten, copper-tungsten, and other electrically conductive materials. Special forms of EDM can now be used to polish tool cavities, produce undercuts, and make conical holes from cylindrical electrodes.

The electroforming process is used for the production of single or low numbers of cavities, as opposed to others requiring many cavities. The process deposits metal on a master in a plating bath. Many proprietary processes exist. The master can be constructed of such materials as plastic, reinforced plastic, plaster, or concrete that is coated with silver to provide a conductive coating. The coated master is placed in a plating tank and nickel or nickel-cobalt is deposited to the desired thickness of up to about 0.64 cm (0.25 in.). With this method, a hardness of up to 46 RC is obtainable. To reinforce the nickel shell it is backed up with different materials (copper, plastic, etc.) to meet different applications. A sufficient thickness of copper allows for machining a flat surface to enable the cavity to be mounted into a cavity pocket.

Tooling surfaces such as mold cavities and die openings require meeting certain surface finishes. Rather than identifying the required finish as dull, vapor-honed satin, shiny, etc., there are standards such as a diamond polishing compound, SPI (originally SPI/SPE) Mold Standard Finish, and American Association's standard B46.1 Surface Texture (extremely accurate surface measurements; a near-perfect system) that are used. This ASA B46.1 corresponds to the Canadian standard CSA B 95 and British standard BS 1134.

A general requirement for all tools is that they have a high polish where the plastic melt contacts the tools.[316, 317] Other parts of the tools may require a degree of polishing (smooth) permitting parts to fit with precision and eliminating melt leaks in the tools. A large part of tool cost is polishing, which can represent from 5 to 30% of the tool cost.

Polishing can damage the tool material unless it is properly done. An example of a common defect is orange-peel. It is a surface wavy effect that results when the metal is stretched beyond its yield point by over polishing and takes a permanent set. Further polishing will only make matters worse with small particles breaking away from the surface. The harder the steel, the higher the yield point and therefore the less chance of orange-peel. Hard carburized or nitrided surfaces are much less prone to this problem. To avoid orange-peel, polish the tool by hand. With powered polishing equipment, it is easier to exceed the yield point of the metal. If power polishing is done, use light passes to avoid overstressing.

Protective coating/plating

There is a distinction between platings and coatings. Generally, thin layers of metals applied to the surface of tool components are considered platings. The application of alloys, fluorocarbons, or fluoropolymers [such as PTFE) (polytetrafluoroethylene (Chapter 2)], or dry lubricants is considered a coating. With few exceptions, treatments involve processes and chemicals that should not be used anywhere near a fabricating machine (because of corrosiveness), and they are best handled by custom plating and treating shops that specialize in their use.

Tool coatings/platings are typically used to enhance tool performance in one or more of the following areas: wear resistance, corrosion resistance, improved tool release, resizes components, and/or their combination. No single treatment is ideal for solving all these problems. Treatments are used that resist the corrosion damage inflicted by chemicals such as hydrochloric acid when processing PVC, formic acid or formaldehyde with acetals, and oxidation caused by interaction between tools and moisture in the plant atmosphere. Release problems require treatments that decrease friction and increase lubricity in mold cavities.[3]

Tools can be subjected to sweating and moisture condensation particularly during the summer months. This can lead to corrosion and rust, and in turn, to poor finishes and inferior quality fabricated products. By keeping the air in the plant or around the tool dry, you can not only eliminate rust but also improve product quality and increase your production rate.

Tool wear cannot be prevented. This wear should be observed, acknowledged during maintenance check-up, and dealt with at intervals in the tool's useful life; otherwise, the tool could be allowed to wear past the point of economical repair. Periodic checks of how platings and coatings are holding up will allow the fabricator to have a tool resurfaced before damage is done to the tool. A poorly finished tool that is being used for the first time, its heat, pressure, and exposure to plastic are actually reworking its surface. Fragmented metal is pulled out of the metal fissures, and plastic forced into them. While the fissures are plugged with plastic, the fabricator may actually be processing plastic against plastic.

Starting up a tool that has a poor finish can damage the tool without proper presurfacing. If the tool surface is unsound (no prior treatment was used although required), a thin layer of metal plating, particularly chrome plating, will not make it correct. A poorly prepared surface makes for poor adhesion between treatment and the base metal. The effectiveness of a surface treatment depends on not only the material being applied, but also the process by which it is applied. For any plating or coating to adhere to the surface of a tool component, it has to bond to the surface. The bonding may be relatively superficial, or a chemical/molecular bond may accomplish it. The nature and strength of the bond directly affect the endurance and wear characteristics of the plating or coating. The experience of the plater is an important factor in applications where cut-and-dried or standard procedures have not been developed.[453, 483]

Mold

Following the product design, a relevant tool (mold or die) needs to be produced. Figures 17.1 and 17.2 provides an introduction to layouts, configurations, and actions of molds (Chapter 4). Alignment of mold halves during their opening and closing actions requires precision mold parts to fabricate quality parts. When possible mold cavity walls are tapered to permit ease of separating molded parts from the cavity. Operations of tools vary from fabricating solid to foamed products such

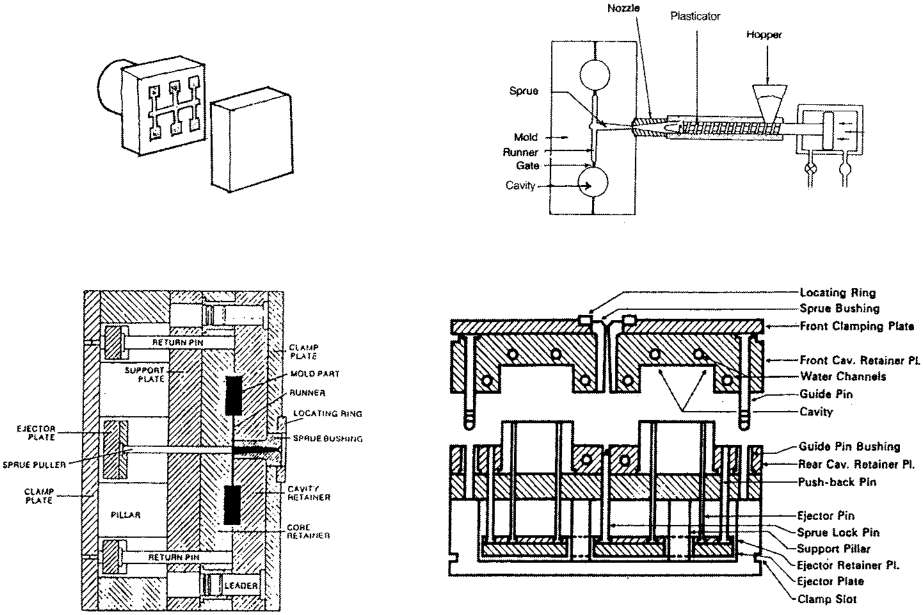

Nozzle
Plasticator
Hopper
Sprue
Mold
Runner
Gate
Cavity
RETURN PIN
CLAMP PLATE
SUPPORT PLATE
MOLD PART
RUNNER
LOCATING RING
EJECTOR PLATE
SPRUE BUSHING
SPRUE PULLER
CAVITY RETAINER
CLAMP PLATE
PILLAR
CORE RETAINER
RETURN PIN
LEADER
Locating Ring
Sprue Bushing
Front Clamping Plate
Front Cav. Retainer Pl.
Water Channels
Guide Pin
Cavity
Guide Pin Bushing
Rear Cav. Retainer Pl.
Push-back Pin
Ejector Pin
Sprue Lock Pin
Support Pillar
Ejector Retainer Pl.
Ejector Plate
Clamp Slot

Figure 17.1 Examples of mold layouts, configurations, and actions

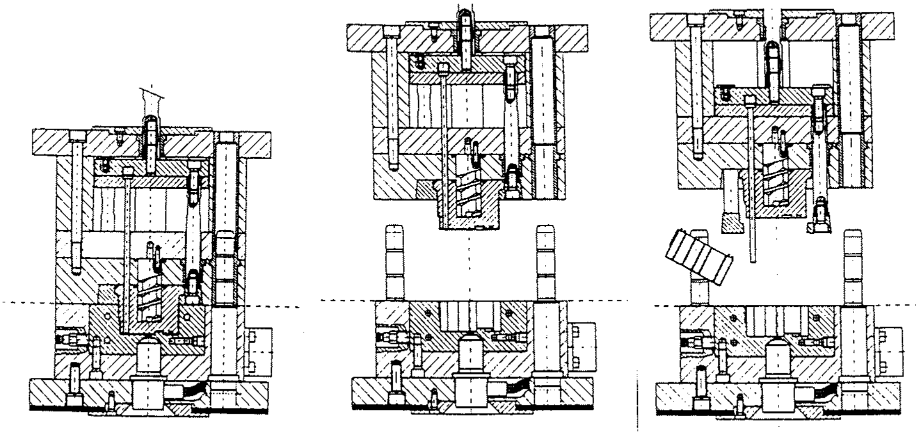


Figure 17.2 Sequence of mold operations

as using a steam chest for producing expandable polystyrene foams (Chapter 8).

There are approaches to simplifying mold design and its action (Figure 17.3). There are different approaches used to mold threaded parts such as bottle caps, medical components, mechanical and electrical connectors, etc. To date most of these molds use mechanical and/or hydraulic (toothed racks, spur-type gears, etc.) unscrewing drive systems. To meet more precise dimensions, more compactness, faster cycle, no oil contamination, and save space unscrewing cores are driven electrically with servomotors. These Programmable Electric Rotating Core (PERC) systems use small motors mounted on the mold.[322]

A mold is an efficient heat exchanger. If not properly designed, handled, and maintained, it will not be an efficient operating device. Hot melt, under pressure, moves rapidly through the mold. Air is released from the mold cavity(s) to prevent the melt from burning, prevent voids in the product, and/or prevent other defects including the molded products service operating performances.[3] In order to solidify the TP, hot melt water or some other media circulates in the mold to remove heat from TPs or higher heat is used with TSs.

The melt flow is largely governed by the shape and dimensions of the product and the location and size of the gate(s). A good flow will ensure uniform mold filling and prevent the formation of layers. Jetting of the plastic into the mold cavity may give rise to surface defects, flow lines, variations in structure, and air entrapment. This flow effect may occur if a fairly large cavity is filled through a narrow gate, especially if a plastic of low melt viscosity is used.[487]

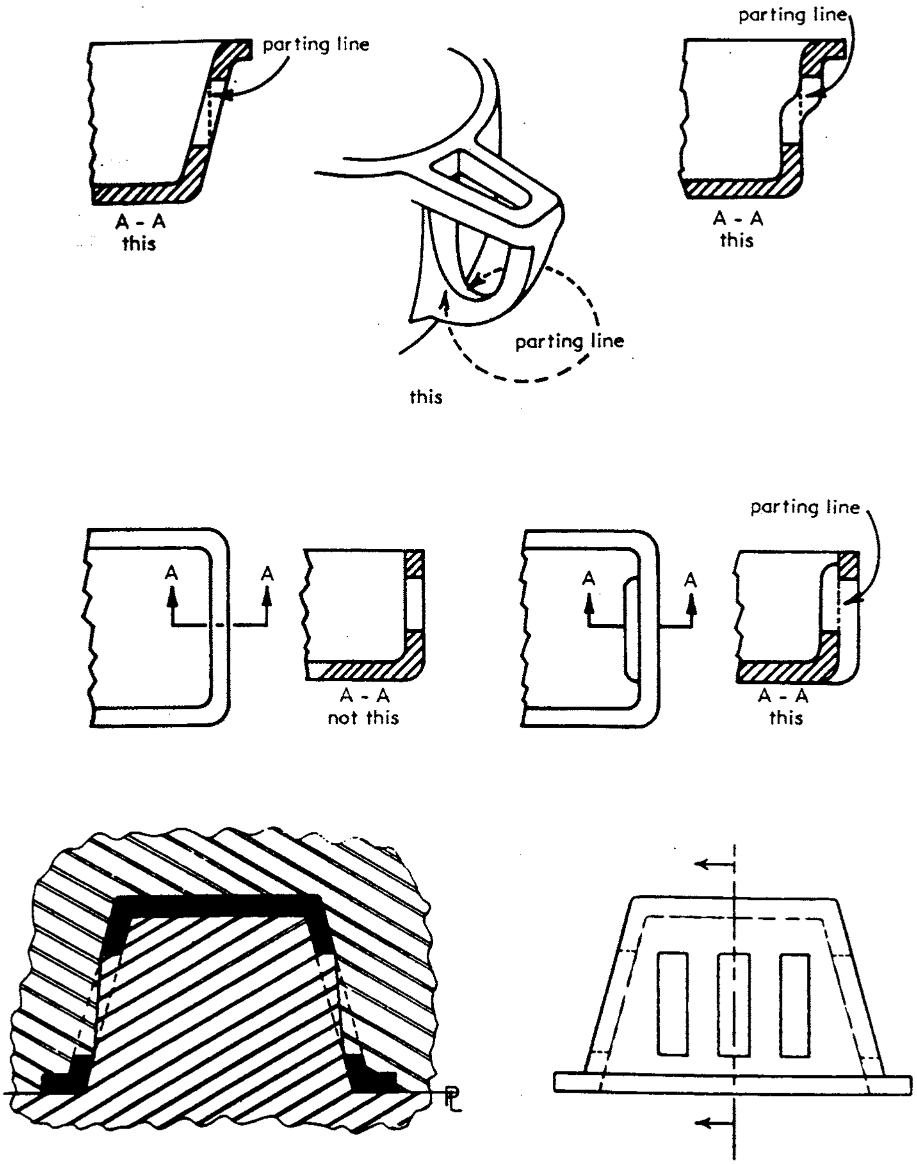

parting line
A - A
this
parting line
this
parting line
A - A
this
A
A
A - A
not this
A
A
parting line
A - A
this
PL

Figure 17.3 Examples to simplify mold design and action

The hot TP melt entering the cavity solidifies immediately upon contact with the relatively colder cavity wall. The solid outer layer thus formed will remain in situ and forms basically a tube through which the melt flows on to fill the rest of the cavity. This accounts for the fact that a rough cavity wall adds only marginally to flow resistance during mold filling. Practice has shown that only very rough cavity walls (sandblasted surfaces) add considerably to flow resistance.[487]

The principal types are two-plate, three-plate, and stack molds. Others include the family mold that has multiple cavities of different shapes in one mold.[3, 324] A further distinction concerns the feed system that can be either the cold or hot type. These classifications overlap. Three-plate molds will usually have a cold runner feed system, and a stack mold will have a hot runner system. Two-plate molds can have either feed system.

The *2-plate mold* opens into two principal parts (Figure 17.2). These are known as the fixed or injection half that is attached to the machine fixed platen, and the moving or ejection half that is attached to the moving platen.[3] This is the simplest type of injection mold and can be adapted to almost any type of molding. The cavities and cores that define the shape of the molding are so arranged that when the mold opens at the parting line (PL), the molding remains on the ejection half of the mold.[325] In the simplest case, this is determined by shrinkage that causes the molding to grip on the core. Sometimes it may be necessary to adopt positive measures such as undercut features or cavity air blast to ensure that the molding remains in the ejection half of the mold.

The *3-plate mold* splits into three principal linked parts when the machine clamp opens (Figure 17.4). As well as the fixed and moving parts equating to the 2-plate mold there is an intermediate floating cavity plate. The feed system is housed between the fixed injection half and the floating cavity plate. When the mold opens it is extracted from the first daylight formed by these plates parting. The cavity and core is housed between the other side of the floating cavity plate and the moving ejection part of the mold. Moldings are extracted from the

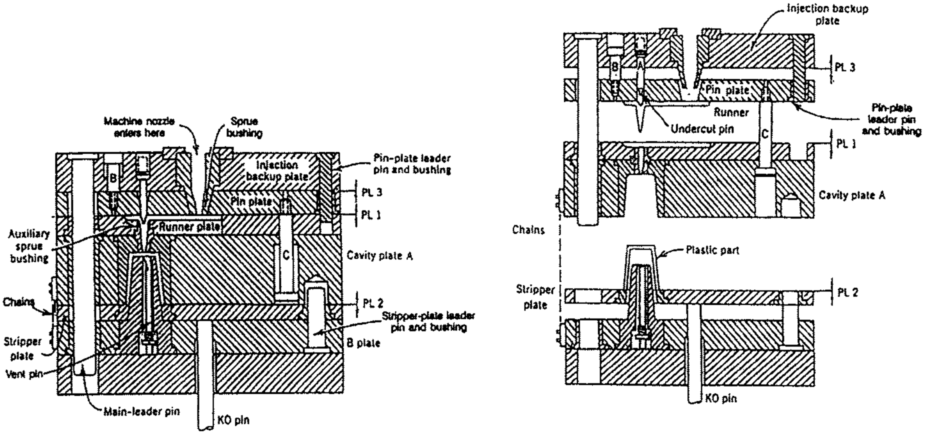

Machine nozzle enters here
Sprue bushing
Injection backup plate
B
Pin-plate leader pin and bushing
PL 3
Pin plate
PL 1
Runner plate
Auxiliary sprue bushing
C
Cavity plate A
Chains
PL 2
Stripper-plate leader pin and bushing
Stripper plate
B plate
Vent pin
Main-leader pin
KO pin
Injection backup plate
B
A
PL 3
Pin plate
Runner
Pin-plate leader pin and bushing
Undercut pin
C
PL 1
Cavity plate A
Chains
Plastic part
Stripper plate
PL 2
KO pin

Figure 17.4 Example of 3-plate mold

second daylight when these plates separate. The mold needs separate ejection systems for the feed system and the moldings. Motive power and opening time for the feed system ejector and the movement of the floating cavity plate is derived from the clamp-opening stroke position by a variety of linkage devices.

The 3-plate mold is normally used when it is necessary to inject multiple cavities in central rather than edge positions and/or to increase the production rate. This is done for flow reasons, to avoid gas traps, ovality caused by differential shrinkage, or core deflection caused by unbalanced flow. This type of mold also has the advantage of automatically removing (degating) the feed system from the molding. The disadvantages are that the volume of the feed system is greater than that of a 2-plate mold for the same component, and that the mold construction is more complicated and costly.

Stack mold also features two or more daylights in the open position. Two daylights are the normal form (Figure 17.5) but up to four are also used; more could be used. The purpose of the stack mold is to increase the number of cavities in the mold without increasing the projected area so the clamp force required from the IMM remains the same. Similar cavities and cores between each of the daylights are normally used.

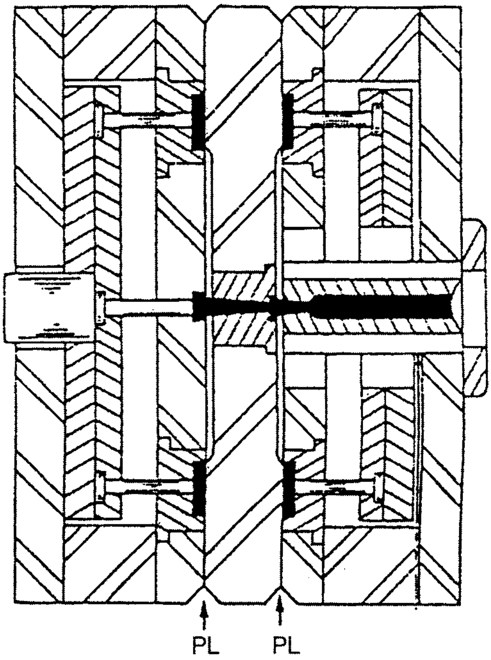


Figure 17.5 Examples of stacked molds

Microscale mold fabrication continues to expand its capability from recent developments in electronic signal sensing, part measurement, and process control. These improvements allow mold makers to produce molds with extremely small cavities and hold tolerances of ±10 nm while cutting mold steel (Chapter 4).[46, 150, 444]

To make tiny features, mold makers can use an unconventional technique such as reactive ion etching, developed at the Georgia Institute of Technology in Atlanta. The mold makers use reactive ions to knock metal atoms out of a mold surface. Mold makers can use lasers to create extremely small features such as small holes that can not be made with a conventional electronic discharge machine (EDM).

New technologies in manufacturing micromolds continue. As an example there is the LIGA. It is a lithography/electroplating technique developed in Germany. Companies are producing LIGA structures that could be converted into molding cavities. This technology allows molds to be minuscule. To date high-volume molding operations using 64-cavity molds limits control of the individual cavities so the parts are not the same. Use is made of two- or four-cavity molds that produce more identical parts.

The *feed system* is the flow melt passage in the mold, between the nozzle of the IMM and the mold cavity (Figure 17.1). This feature has a considerable effect on both the quality and economy of the molding process. The feed system must conduct the plastics melt to the cavity via a *sprue, runner, and gate* at the correct temperature/pressure/time period, must not impose an excessive pressure drop or shear input, and should not result in non-uniform conditions at the cavities of multi-impression molds.

The feed system is an unwanted by-product of the molding process, so a further requirement is to keep the mass of the feed system at a minimum to reduce the amount of plastic used. This last consideration is a major point of difference between *cold and hot runner* systems. The cold runner feed system is maintained at the same temperature as the rest of the mold. In other words, it is cold with respect to the melt temperature. The cold runner solidifies along with the molding and is ejected with it as a waste product in every cycle. The hot runner system is maintained at melt temperature as a separate thermal system within the cool mold. Plastic material within the hot runner system remains as a melt throughout the cycle, and is eventually used on the next cycle. Consequently, there is little or no feed system waste with a hot runner system. Effectively, a hot runner system moves the melt between the machine plasticizing system and the mold to a point at or near the *cavity*(s).[3, 32, 326–332, 490]

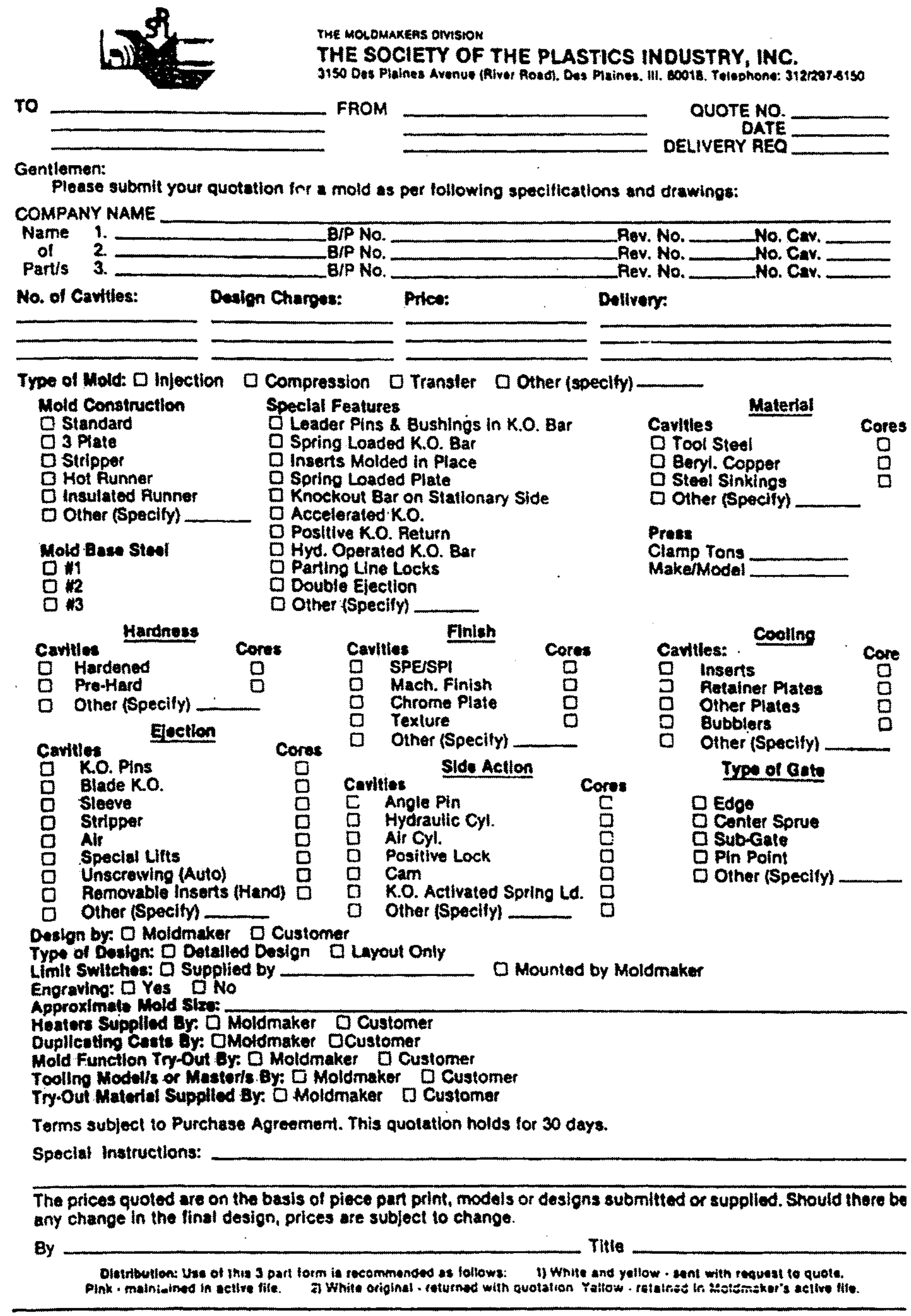
In the past perhaps the least-understood and least well applied factor is the inclusion of cooling channels to meet proper heat transfer from the plastic melt to the cooling liquid (for thermoplastics). Usually, insufficient space is allowed between cavities, particularly in molding the crystalline plastics (Chapter 1). Plastic melt-cooling rate is usually the final control in the variable associated with the final plastic product performances. This variable influences factors such as melt flow rate, residual stress, and degree of orientation. Heating and cooling rates for amorphous and crystalline plastics differ. If not properly controlled, product performances are either not meeting maximum values or they are defective.[3]

Cooling channels can represent a real difficulty in mold design. Core and cavity inserts, ejector pins, fasteners, and other essential mechanical features all act as constraints on the positioning of cooling channels, and all seem to take precedence over cooling. However, uniform and efficient cooling is crucial to the quality and economy of the molding, so channel positioning must take a high priority in the total mold design.

Cooling channel design is inevitably a compromise between what is thermally ideal, what is physically possible, and what is structurally sound. The thermal ideal would be flood cooling over the entire area of the molding, but the pressurized mold cavity would be unsupported and mechanical details like ejectors could not be accommodated. [Flood cooling is included as a cooling method for blow molding (Chapter 6)]. Interrupting the flood-cooling chamber with supporting ribs could provide support, but the mold construction is complicated by the need to fabricate and seal the cooling chamber. An important consideration in cooling channel design is to ensure that the coolant circulates in turbulent rather than laminar flow. The coefficient of heat transfer of the cooling system is drastically reduced in laminar flow. The Reynolds number (Re or N_{re}.) determines the condition of laminar or turbulent flow.[3]

Mold makers and/or molding machinery manufacturers can provide information concerning safety. American Society for Metals (ASM) is helpful by providing a checklist. It involves the startup and shutdown of an injection molding machine. The Mold Safety Committee of the Society of the Plastics Industry, Inc. (SPI) subcommittees ensures that molds meet certain guidelines for safety and good electrical practices. These groups, organized under the SPI Moldmakers Division, address different issues applicable to the mold and its operation. It points out the various difficulties that can result, unless thorough understanding and communication are established between the mold buyer (molder) and moldmaker. Table 17.2 is the SPI Moldmakers Division quotation guide.

Table 17.2 SPI Moldmakers Division quotations guide



THE MOLDMAKERS DIVISION
THE SOCIETY OF THE PLASTICS INDUSTRY, INC.
3150 Des Plaines Avenue (River Road), Des Plaines, Ill. 60018, Telephone: 312/297-6150

TO ______________________ FROM ______________________ QUOTE NO. ________
______________________ ______________________ DATE ________
______________________ ______________________ DELIVERY REQ ________

Gentlemen:
Please submit your quotation for a mold as per following specifications and drawings:

COMPANY NAME ______________________

Name of Part/s
1. ______________ B/P No. ______________ Rev. No. ______ No. Cav. ______
2. ______________ B/P No. ______________ Rev. No. ______ No. Cav. ______
3. ______________ B/P No. ______________ Rev. No. ______ No. Cav. ______

No. of Cavities:	Design Charges:	Price:	Delivery:
______	______	______	______
______	______	______	______
______	______	______	______

Type of Mold: ☐ Injection ☐ Compression ☐ Transfer ☐ Other (specify) ______

Mold Construction
- ☐ Standard
- ☐ 3 Plate
- ☐ Stripper
- ☐ Hot Runner
- ☐ Insulated Runner
- ☐ Other (Specify) ______

Mold Base Steel
- ☐ #1
- ☐ #2
- ☐ #3

Special Features
- ☐ Leader Pins & Bushings in K.O. Bar
- ☐ Spring Loaded K.O. Bar
- ☐ Inserts Molded in Place
- ☐ Spring Loaded Plate
- ☐ Knockout Bar on Stationary Side
- ☐ Accelerated K.O.
- ☐ Positive K.O. Return
- ☐ Hyd. Operated K.O. Bar
- ☐ Parting Line Locks
- ☐ Double Ejection
- ☐ Other (Specify) ______

Material

Cavities		Cores
☐	Tool Steel	☐
☐	Beryl. Copper	☐
☐	Steel Sinkings	☐
☐	Other (Specify) ______	

Press
Clamp Tons ________
Make/Model ________

Hardness

Cavities		Cores
☐	Hardened	☐
☐	Pre-Hard	☐
☐	Other (Specify) ______	

Ejection

Cavities		Cores
☐	K.O. Pins	☐
☐	Blade K.O.	☐
☐	Sleeve	☐
☐	Stripper	☐
☐	Air	☐
☐	Special Lifts	☐
☐	Unscrewing (Auto)	☐
☐	Removable Inserts (Hand)	☐
☐	Other (Specify) ______	

Finish

Cavities		Cores
☐	SPE/SPI	☐
☐	Mach. Finish	☐
☐	Chrome Plate	☐
☐	Texture	☐
☐	Other (Specify) ______	

Side Action

Cavities		Cores
☐	Angle Pin	☐
☐	Hydraulic Cyl.	☐
☐	Air Cyl.	☐
☐	Positive Lock	☐
☐	Cam	☐
☐	K.O. Activated Spring Ld.	☐
☐	Other (Specify) ______	☐

Cooling

Cavities:		Core
☐	Inserts	☐
☐	Retainer Plates	☐
☐	Other Plates	☐
☐	Bubblers	☐
☐	Other (Specify) ______	

Type of Gate
- ☐ Edge
- ☐ Center Sprue
- ☐ Sub-Gate
- ☐ Pin Point
- ☐ Other (Specify) ______

Design by: ☐ Moldmaker ☐ Customer
Type of Design: ☐ Detailed Design ☐ Layout Only
Limit Switches: ☐ Supplied by ______________ ☐ Mounted by Moldmaker
Engraving: ☐ Yes ☐ No
Approximate Mold Size: ______________________
Heaters Supplied By: ☐ Moldmaker ☐ Customer
Duplicating Casts By: ☐ Moldmaker ☐ Customer
Mold Function Try-Out By: ☐ Moldmaker ☐ Customer
Tooling Model/s or Master/s By: ☐ Moldmaker ☐ Customer
Try-Out Material Supplied By: ☐ Moldmaker ☐ Customer

Terms subject to Purchase Agreement. This quotation holds for 30 days.

Special Instructions: ______________________

The prices quoted are on the basis of piece part print, models or designs submitted or supplied. Should there be any change in the final design, prices are subject to change.

By ______________________ Title ______________________

Distribution: Use of this 3 part form is recommended as follows: 1) White and yellow - sent with request to quote. Pink - maintained in active file. 2) White original - returned with quotation Yellow - retained in Moldmaker's active file.

In this age of specialization, the purchasing community has found it increasingly difficult to locate the right source for the right job. To assist, the Moldmakers of the SPI provides industry with an updated directory of its members and their special capabilities. The SPI Moldmaker members are in constant contact with the plastics industry and its ever-changing technology. The directory lists moldmakers as contract or custom services and in turn by type of process mold such as injection molding and blow molding.

There are also publications that provide buyer guides: Plastics News provides information; Moldmaking Technology magazine issues an annual buyers guide that features directories on:

1 mold making equipment, supplies, and accessories,
2 mold components,
3 mold design and engineering equipment,
4 mold material,
5 machining equipment,
6 electrical discharge machining equipment and Supplies,
7 machining tools and accessories,
8 hot runner systems and supplies
9 mold polishing and repair equipment and supplies.[410, 452, 490]

Die

Introduction

This review primarily concerns extruder dies. They are devices, usually of steel, having an orifice (opening) with a specific shape or design geometry which it imparts to a plastic melt extrudate pumped from an extruder under pressure. The die opening settings influences properties of the extruded plastic. Dies have a specific orifice (opening) with a specific shape so that different products can be produced such as sheets, films, pipes, tubings, profiles, wire coatings, filaments, etc. These steel precision works of art have at least a mirror finish on the melt flow channel orifice surfaces. In addition to information presented here there is additional information on dies in Chapter 5.

The function of a die is to accept and control the available melt (extrudate) from an extruder and deliver it to downstream takeoff equipment as a shaped product (profile, film, sheet, pipe, filament, etc.). Target is to minimize deviation in cross-sectional dimensions, smooth surfaces, and a uniform output by weight at the fastest possible rate. In order to do this, the extruder must deliver melted plastic to the die targeted to be a so-called ideal mix at a constant rate, temperature, and pressure. Measurement of these variables is required and usually carefully performed (Chapter 5).

The die has substantial influences on the plastic due to the melt flow orientation of the molecules, such as having different properties parallel (machine direction) and perpendicular to the flow direction. These differences have a significant effect on the performance of the product. The die designs with melt condition (pressure, temperature, rate of travel, etc.) and its downstream equipment can provide the required unidirectional, bidirectional, or desired properties. The pressure usually ranges as follows:

1 blown and lay-flat films at 14 to 40 MPa (2,000 to 5,800 psi);
2 cast film, sheet, and pipe at 3.5 to 27.6 MPa (500 to 4,000 psi);
3 wire coating at 10 to 55 MPa (1,450 to 8,000 psi);
4 monofilament at 7 to 21 MPa (1,000 to 3,000 psi).

As with molds, metals are used such as for flat film and sheet dies that are normally constructed of medium-carbon alloy steels. The flow surfaces of the die usually have protective coatings such as chrome plating to provide corrosion resistance. With proper chrome plated surfaces, microcracks that may exist on the steels are usually covered. The exterior of the die is generally flash chrome plated to prevent rusting. Where chemical attack can be a severe problem (processing PVC, etc.), various grades of stainless steels are used with special coatings. Coatings will eventually wear, so it is important that a reliable plater properly recoat the tool, usually the original tool manufacturer.

Die material is almost exclusively steel because of the many factors that must be satisfied. The non-alloy steels such as AISI 1040 and other common steels can be used for simple dies such as tubing and profile dies where the ease of machining and low cost are suitable for the relatively small sizes and unsophisticated applications. Alloy steels such as AISI 4140 and other similar alloys are used for the majority of die applications because they meet most requirements along with an inherent high quality and lack of inclusions, pits, voids, and hard/soft spots. The lack of corrosion- and rust-resistance of alloy steel is a potential weakness but is easily overcome by plating normally with chrome. High-nickel alloy steels are used when certain plastics, such as PVC and PVDC, can degrade with temperature and time to produce acids that will corrode plated alloy steels. High-nickel alloy steels provide good corrosion resistance without plating and simplify manufacturing, cleaning, and repair. Stainless steel also is used with degradable materials. Profile, pipe, blown film, and wire coating dies are examples of dies generally constructed of hot-rolled steel for low pressure melt applications.

These steel precision works of art have at least a mirror finish on the melt flow channel orifice surfaces. The slightest minute scratches can produce flaws in the extruded products. Great care must be used during their installation, operation, removal, cleaning, and storage. When designing them the target is to use as few parts as possible. The dies should be easily lifted for installation or maintenance, easily disassembled, easily cleaned, and easily reassembled.

Initial target is to simplify and minimize detractors. The major detractor is to understand melt flow behavior within the die and on exiting the die. Being involved with the product designer usually permits concessions to be made resulting in simplifying and reducing their cost (Chapter 5).

An important characteristic is that the die orifices shape effects melt flow patterns. The effects of the orifice are related to the die design (land length, etc.) and melt condition. As an example using the popular coat hanger-die for fabricating flat sheet, cooling is more rapid at the corners; in fact, a hot center section could cause a product to blow outward and/or include visible or invisible vacuum bubbles (Figure 17.6). With proper orifice shape and melt control (temperature, pressure, and rate of flow) the coathanger and T-type sheet exits the die without these problems.

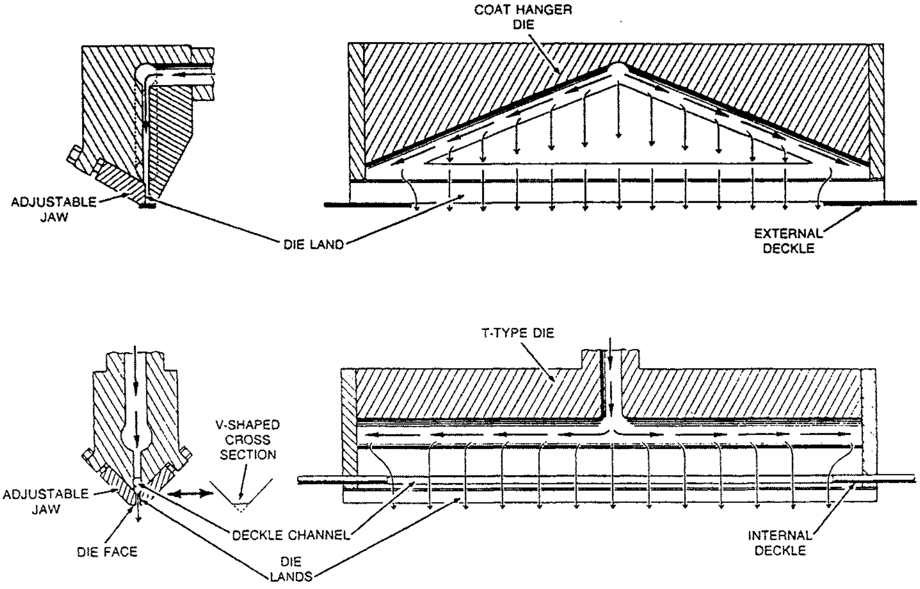


Figure 17.6 Examples of melt flow patterns in a coathanger and T-type die

Each sheet die has limitations for certain type melts such as:

1 the so-called fishbone die has a reduction in its land restriction that can make it basically difficult with most melts for producing a uniform melt distribution,
2 T-type die with high viscosity melts does not produce a uniform distribution, however it is used with high temperature coating, low viscosity melts that result in an acceptable distribution, and
3 coathanger die provides a uniform distribution; it is in common use even though it is more expensive.

The non-Newtonian behavior of plastic melt makes its flow through a die complicated but controllable within certain limits (Chapter 3). Simplified flow equations are available to account for the non-Newtonian melt behavior. They provide an excellent foundation using an empirical approach that pertains to extrusion die channels of different shapes.

The melt in the die is under pressure. Upon exiting the die and the pressure is released, it expands in all directions. The amount of expansion can be reduced, based on the die design such as its land length, also melt temperature and rate of flow through the die and rate of pull from the die. Figure 17.7 provides an introduction to this melt behavior. By maximizing performance of plastic melts, die designs, and takeoff equipment (rate of travel, cooling rate, etc.) dimensional tolerances can usually be held to within at least ± 3 to 5%. Tighter tolerance is achieved using suitable takeoff equipment.

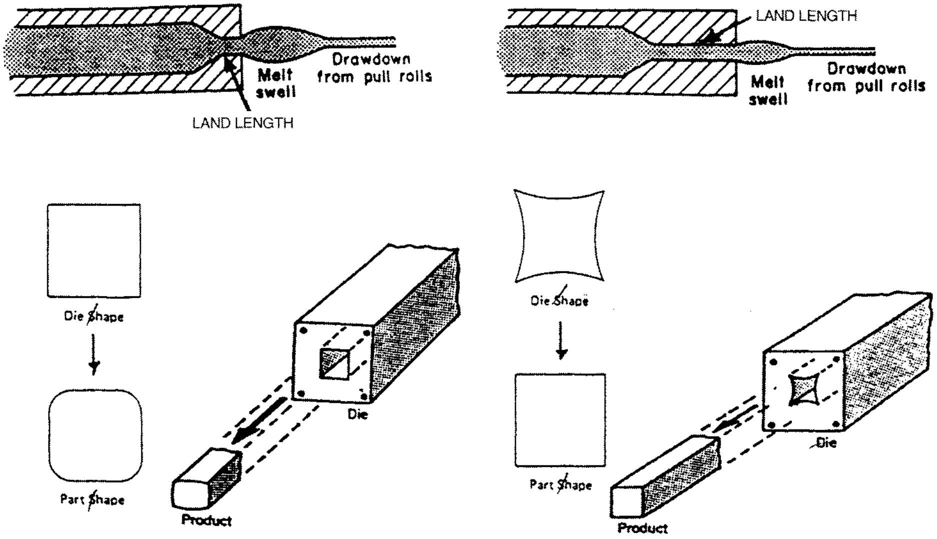


Figure 17.7 Examples of melt flow behavior

The approach used for shaping orifices in the dies is important requiring 3-D evaluation that includes streamlining. Where possible, all dies should be groomed to promote streamlined melt flow and avoid the obvious pitfalls associated with the areas that could cause stagnation such as right angle bends, sharp corners, and sections where flow velocities are diminished and are not conducive to streamlined flow. The target is to avoid these design faults. Stagnation areas from non-streamline/flat plate dies can easily cause accumulation of melt that will degrade and effect the extrudate.

There are different approaches to developing the streamlined shapes. They range from totally trial-and-error to finite element analysis (FEA). The trial method usually involves gradually cutting or removal of the die orifice metal. Between cuts an examination is made of the extrudate and the metal cavity surface to check on melt hang-ups, melt burning, streaks, and other stagnating problems. With FEA, and using appropriate rheological plastic data (Chapter 1), one can easily determine an approach to a streamline flow pattern that may be acceptable even without minor adjustment.[1]

With streamlining a variety of advantages exist such as:

1 dies can operate at higher outputs;

2 pressure drops are lower and more consistent over a range of melt temperatures and pressures;

3 generally the melt uniformity across the extrudate is more uniform and shape control is enhanced; and

4 sometimes crucial for high production output rates where plastics have limited stability and causes hang-ups/degradation going through non-streamlined dies.

There are many equations that relate to melt flow and in turn to orifice shapes.[143] Off the shelf computer software programs are available[333, 334, 476] with certain die designers/manufacturers having their own very successful software. Analyzing melt flow in dies is rather complicated and difficult. Using available CAD programs can be extremely helpful but what really helps is experience in the design and use of different dies with the different plastics. Industry has specialists in-house or specialty die manufacturers that produce efficient operating dies used to extrude all types of products. What makes it difficult is the nature of the plastic melts that are not perfect.

The following review uses an updated equation obtained through the available high-speed computer study during the early 1960s by G. P.

Lahti.[335] He did this work at DuPont and later went to NASA. It provides an excellent foundation using an empirical approach that pertains to extrusion die channels of several shapes. As shown in Figure 17.8, the following equations can be used:

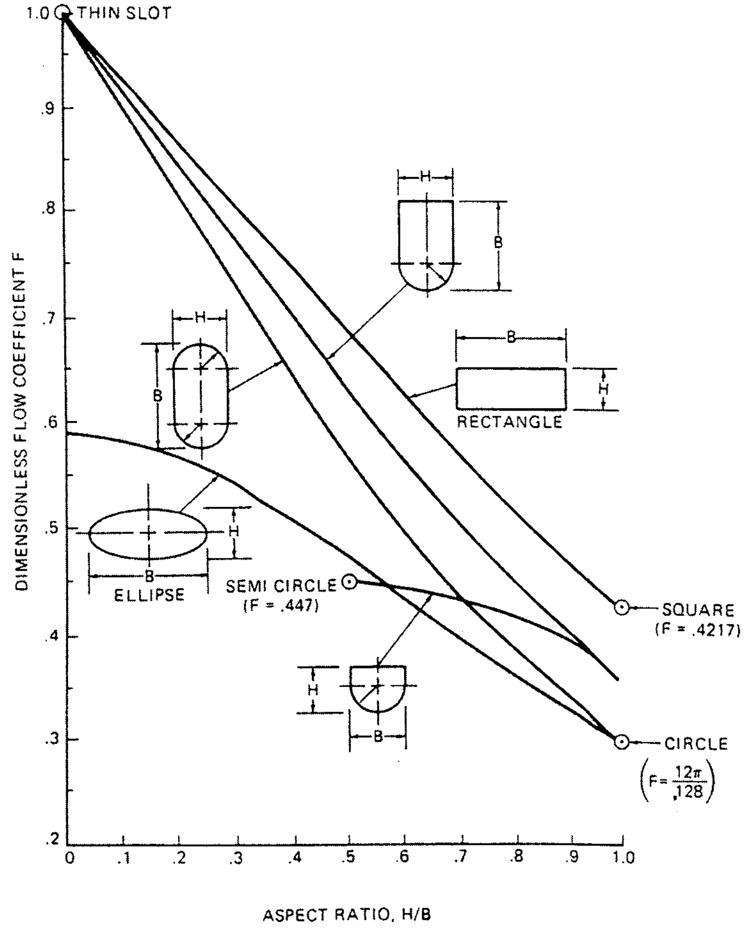


Figure 17.8 Flow coefficients calculated at different aspect ratios for various shapes using the same equation

$$Q = (1/\mu)\ (\Delta P/L)\ (BH^3/12)\ (F) \text{ or } \Delta P = (12\mu QL/BH^3)\ (1/F)$$

where: Q = volumetric flow rate, ΔP = pressure drop, L = length of channel, B = maximum dimension of cross section, B = ≥H, in. (mm), H = minimum dimension of cross section, in. (mm), and F = flow coefficient.

Using this approach and account for the entrance effect when a melt is forced from a large reservoir, the channel length (L) must be corrected or the apparent viscosity must be used once it has been obtained from shear rate–shear stress curves for the L/H value of existing channel. Entrance effect becomes negligible for L/H > 16.

By developing the product's geometry and determining plastic viscosity and pressure drop, the volumetric flow rate (Q) can be calculated.[143] For the shape shown the following calculation is used: Calculations can also be used for:

1 flow in two or three directions which exists in a tapered die,

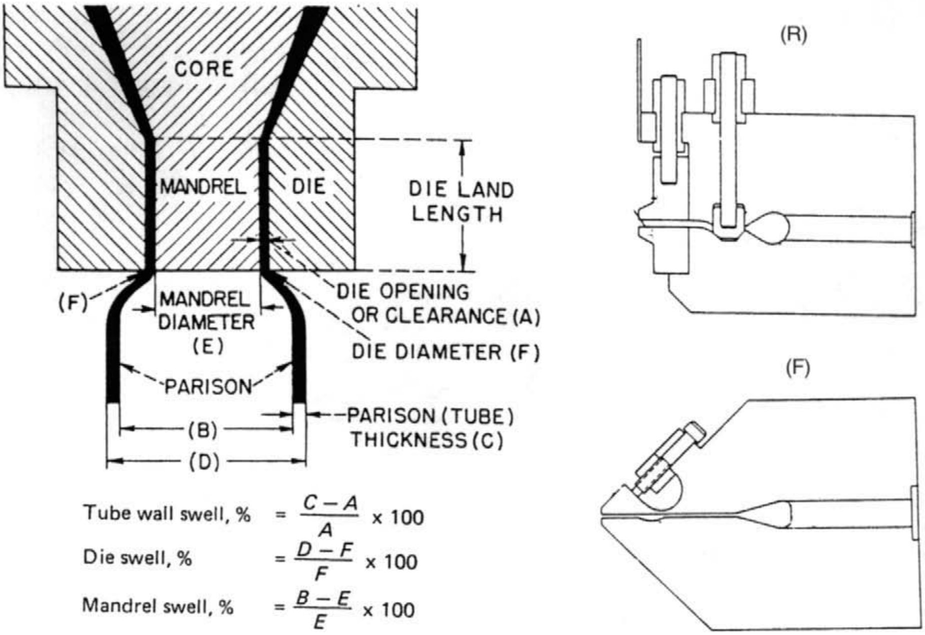
2 detailed discussion including limitations and assumptions for regular and irregular shapes are made for slow viscous melts, and

3 so forth.

Each melt basically has its own plus and minus capabilities for operating in the die melt channels following its non-Newtonian behaviors (Chapter 1). The extruders (and other equipment) have their limitations, such as heat transfers through metal parts and metal parts that are subjected to wear. Therefore, what tends to exist is an empirical science that continues to work efficiently. The limitations have always existed. But with time as material and equipment developments occur, designing dies, as well as operating equipment, continues to improve by increasing product performances and output rates.[449–455]

With extruded melt from the die, there is usually some degree of swelling (Figure 17.7). To eliminate or significantly reduce the swell to an acceptable amount, stretching or drawing the extrudate to a size equal or smaller than the die opening occurs. The dimensions are targeted to be reduced proportionally so that the drawdown section is the same as the original section but smaller proportionally in each dimension. However, the effects of melt elasticity mean that the plastic does not drawdown in a simple proportional manner; thus adjustments are made in the orifice opening, melt condition, and/or downstream equipment. These type variations are significantly reduced in a circular extrudate, such as pipe and wire coating.

The die land is the parallel section just before the exit of the die head in the direction of the melt flow. It is usually expressed as the ratio between the length of the opening in the flow direction and the die opening; expressed as an example 10:1. It is vital to shaping the extrudate and providing thickness dimensional control. A very important dimension is the length of the relatively parallel die land. In general, it should be made as long as possible. However, the total resistance of the die should not be increased to the point where excessive power consumption and melt overheating occur (Figure 17.9).



$$\text{Tube wall swell, \%} = \frac{C-A}{A} \times 100$$

$$\text{Die swell, \%} = \frac{D-F}{F} \times 100$$

$$\text{Mandrel swell, \%} = \frac{B-E}{E} \times 100$$

Figure 17.9 Example of the land in an extrusion blow molding die that can have a ratio of 10 to 1 and film or sheet rigid (R) and flexible (F) die lip land

The required land length depends not only on the type and temperature of the TP melt, but also on the flow rate. The deformation of the melt in the entry section of the die invariably causes strains that only gradually decrease with time (relaxation). Usually the target is to allow the melt to relax before leaving the die. Otherwise the product dimensions and the mechanical properties may vary, particularly with rapid cooling.

Process control provisions should be made to accurately control melt flow via temperatures, pressures, and rate of flow in all parts of the manifold and die using sensors such as stock thermocouples and pressure transducers (Chapter 3). As an example Extrusion Dies, Inc. (EDI) design film dies, particularly for thick gauge control, combining automatic thermal and mechanical die tuning.[476] Provisions should be made to accurately control temperatures in all parts of the extruder head and die. Plus or minus one degree C or F is typically used in today's temperature control systems. If there is a cold area in the die, the melt flow in that area will be slow and the result will be thin gauge. Hot area results in more flow and the potential to burn (degradation) the plastic exiting.

With microprocessor-based extruders and process lines, die temperature control can easily be accomplished without discrete controllers.

Microprocessor control generally results in less operator attention required, higher levels of reliability, and ease of changing groups of set points. Other advantages are automatically programmed startup sequences, over temperature alarm, thermocouple loss alarm, heater failure alarms, and closer temperature control accuracy (Chapter 3).

Die Type

Different types of dies are required to produce the many different shapes produced by extruders worldwide. Table 17.3 is an example of the few types of dies designed and manufactured by Extrusion Dies, Inc.

Dies can be categorized by their product performance. There are straight through, crosshead, and offset dies. To be more specific they can be classified as:

1 axial or straight through extrusion heads with symmetrical flow channels, particularly tube and pipe heads, circular rod and monofilament dies,

2 angled dies particularly crossheads and angular heads for wire and cable covering, crossheads and offset heads for tube and pipe, and film blowing heads,

3 profile dies that include slot dies for flat film and sheet, and multi-orifice heads for monofilaments;

4 dies for special products such as netting.

The following general classification may be helpful as a guide to film and sheet thickness selection for a die even though different groups within the different industries may have their own thickness definitions as well as their own terminology:

1 film dies are generally applicable for thicknesses of 0.010 in.(0.003 mm) or less,

2 thin gauge sheet dies are normally designed for thicknesses up to 0.060 in. (0.015 mm),

3 intermediate sheet dies may cover a thickness range of 0.040 to 0.250 in. (0.01 to 0.06 mm); and

4 heavy gauge sheet dies extrude thicknesses of 0.080 to 0.500 in. (0.02-to 0.13 mm).

The coupling between barrel and die can be carried out in various ways using bolts or locking devices. They include:

Table 17.3 Examples of extrusion dies (courtesy of Extrusion Dies, Inc.)

EDI Model No.	*Flex Range*	*Restrictor Bar*	*Film 10 ml & Below (254 μm & Below)*	*Coating & Laminating*	*Thin Sheet 10 ml–60 ml (254 μm–1524 μm)*	*Midrange Sheet 10 ml–90 ml (254 μm–2286 μm)*	*Heavy Sheet 60 ml & Above (1524 μm & Above)*	*Lab. Applications*	*Options*
Ultraflex L 40	0.040 in (1.0 mm)		■	■				■	Lip adjustments
Ultraflex L 75	0.075 in (1.9 mm)				■			■	Micro push
Ultraflex 40	0.040 in (1.0 mm)		■	■					Micro push/pull
Ultraflex H 40	0.040 in (1.0 mm)		■	■					Material of construction
Ultraflex H 75	0.075 in (1.9 mm)				■				Stainless steel
Ultraflex H 100	0.100 in (2.54 mm)				■	■			Other upon request
Ultraflex HM 40	0.075 in (1.9 mm)		■	■					Platings
Ultraflex HM 75	0.075 in (1.9 mm)				■				Electroless nickel
Ultraflex HM 100	0.100 in (2.54 mm)				■	■			Polymer impregnated chrome
Ultraflex H 40 EPC	0.040 in (1.0 mm)		■	■					Polymer impregnated nickel
Ultraflex H 40 EPC C/L	0.040 in (1.0 mm)		■	■					Deckling
Ultraflex LR 40	0.040 in (1.0 mm)	45°	■					■	Removable lips
Ultraflex LR 75	0.075 in (1.9 mm)	45°			■		■	■	Extended lips for
Ultraflex R 75	0.075 in (1.9 mm)	45°*			■		■		close approach
Ultraflex HR 75	0.075 in (1.9 mm)	45°*			■		■		Roll guard
Ultraflex RC 75	0.075 in (1.9 mm)	45°*			■		■		Wrench guard
Ultraflex HRC 75	0.075 in (1.9 mm)	45°*			■		■		Insulation jacket
Ultraflex HRMC 75	0.075 in (1.9 mm)	45°*			■		■		Lip heaters
Ultraflex R 100	0.100 in (2.54 mm)	45°*			■	■	■		Heat tubes

* Also available with 90° restrictor bar.

1 flange fitting with a clamp ring on the barrel and a fixed flange on the die,
2 flanges on the barrel and die with tapered links and two bolted half-clamps, or a ring clamp hinged at one side and bolted to the other side, and
3 swing-bolt flange connection between the barrel flange and a die flange.

Flat Die

The flat dies, or slot dies as they are sometimes called, are used to produce webs in a variety of processes. They all have an interior manifold for distributing the plastic and lips for adjusting the final profile of the web (extrudate). Some dies have movable restrictor bars for changing the manifold for proper melt distribution (Figure 17.10). All flat dies have flexible lips that can be adjusted by bolts to remove humps or bumps in the web's profile. Die lips can have their adjustment bolts push only, where internal plastic melt pressures are adequate to keep the lips positioned against the bolts, or can be push/pull for low pressure applications. Direct acting or differential thread designs (for minute adjustments) are available. Profile variations of at least ± 3% or less can be achieved with flat dies.

To compensate for variable neck-in or to change web widths, flow barriers called deckles can be fitted to the lips at the ends of the die slot. Deckles cannot be used with degradable materials since there is a stagnant region formed behind the deckle that will eventually decompose the plastic. Deckles can be designed to be adjusted while running or adjusted when off-line.[143]

Computer-controlled automatic profile dies with electrical controlled sensors in closed-loop control systems have developed greater efficiency and accuracy to extrusion coating, cast film, and sheet lines. A scanner measures the web thickness and signals the computer, which then converts the readings to act on thermally actuated die bolts. The individual adjusting bolts expand or contract as ordered by the computer to control the profile. The more sophisticated systems measure adjusting bolt temperature and provide faster response time with less scrap and quicker startups. The scanner is typically an infrared, nuclear, or caliper-type gauge.

Cast Film Die

Coathanger interior manifold design with center entry is generally used which promotes good flow patterns without using restrictor bars. Lip gaps are relatively small since most cast films are thin. Push-only bolts are usually enough to control die lips. Drawdown ratios of 20:1 to 40:1 and rates of 20 lb./in. of opening are common. Deckling is usually not

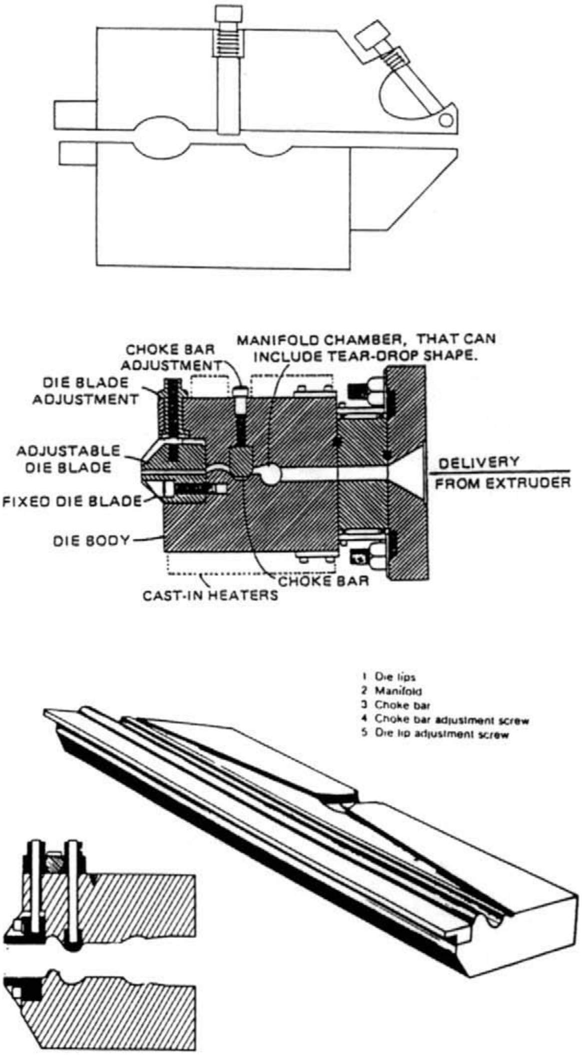

MANIFOLD CHAMBER, THAT CAN INCLUDE TEAR-DROP SHAPE.
CHOKE BAR ADJUSTMENT
DIE BLADE ADJUSTMENT
ADJUSTABLE DIE BLADE
FIXED DIE BLADE
DIE BODY
DELIVERY FROM EXTRUDER
CHOKE BAR
CAST-IN HEATERS
1 Die lips
2 Manifold
3 Choke bar
4 Choke bar adjustment screw
5 Die lip adjustment screw

Figure 17.10 Examples of a flat die with its controls

required.[143] The lips are usually ground to a 16 RMS finish since the chill rolls downstream equipment determine the final finish of the film.

Sheet Coathanger Die

Many characteristics of cast film dies carry over into sheet dies but because of generally thicker materials, die lip openings are much larger and do not generate enough back pressure for accurate distribution of melt (Figure 17.6). Therefore, many sheet dies have a restrictor bar.[143]

Coating and Laminating Die

Extrusion coating dies are simplified by the fact that most plastics run are polyolefins that are substantially nondegradable. This allows use of non-contoured straight manifolds and deckles, but requires high precision based upon the extremely thin coatings desired. In addition, very high operating temperatures can create warpage, corrosion, and control problems. Adjustable-while-running deckles are most common and edge bead reduction techniques can be incorporated. Push-pull die bolts usually are necessary since temperatures are high, viscosities low, and internal pressures low. Multimanifold dies for coextrusion are more commonly used in extrusion coating as well as automatic profile control.

Tubular Die
Examples follow.

Blown Film Die
To eliminate spiders in the die and the inherent film weakness, the spiral mandrel die is used (Figure 17.11). This design usually is computer calculated since the flows and pressure drops are complicated.

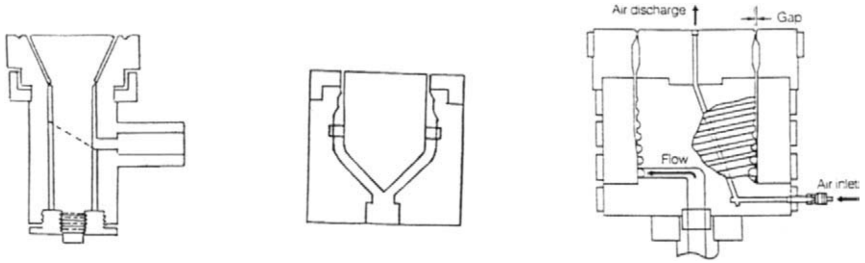


Figure 17.11 Examples of single layer blown film dies include side fed type (top left), bottom fed with spiders type (top center) and others are spiral fed types

When compared to other blown film dies they each have advantages and disadvantages:

1 **side feed die**: *Advantages* – low initial cost, adjustable die opening, and will handle low flow plastics; *Disadvantages* – mandrel deflects with extrusion rate, necessitating die adjustment, die opening changes with pressure, non-uniform melt flow, cannot be rotated, and a weld line in film;

2 **bottom feed spider die**: *Advantages* – positive die opening, can be rotated, and will handle low flow plastics; *Disadvantages* – high initial cost, very difficult to clean, and two or more weld lines in film.

3 **spiral feed die**: *Advantages* – no weld line in film, positive die opening, easy to clean, can be rotated, and improved film optics;

Disadvantages – high head pressure and will not handle low flow resins without modification; high cost.

Pipe Die

Processing can use spider dies, spiral mandrel dies, or basket-type dies that support the inner mandrel with a perforated sleeve through which the melt flows. Figure 17.12 provides examples of different die designs.

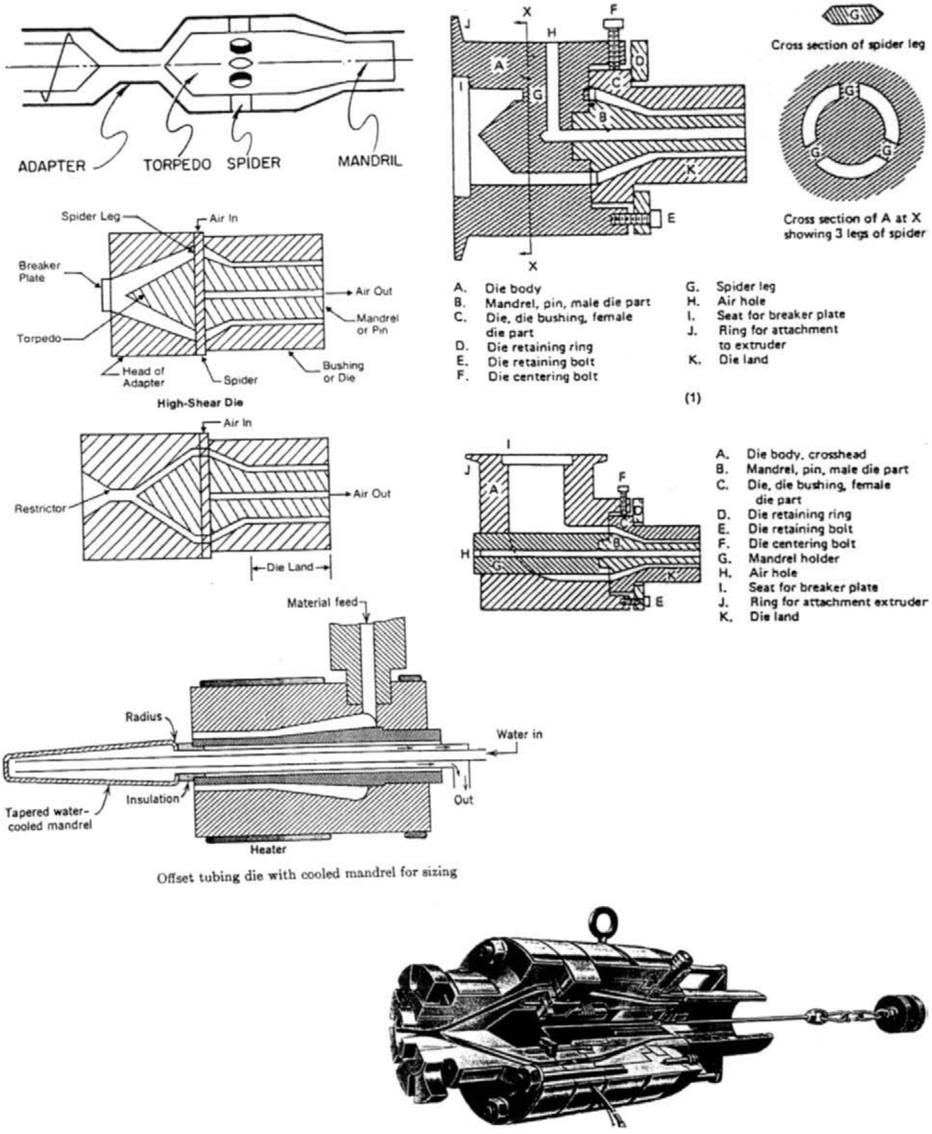

ADAPTER
TORPEDO
SPIDER
MANDRIL
Spider Leg
Air In
Breaker Plate
Air Out
Mandrel or Pin
Torpedo
Head of Adapter
Spider
Bushing or Die
High-Shear Die
Air In
Restrictor
Air Out
Die Land
X
F
J
H
A
D
C
I
G
B
K
E
X
Cross section of spider leg
G
G
G
G
Cross section of A at X showing 3 legs of spider
A. Die body
B. Mandrel, pin, male die part
C. Die, die bushing, female die part
D. Die retaining ring
E. Die retaining bolt
F. Die centering bolt
G. Spider leg
H. Air hole
I. Seat for breaker plate
J. Ring for attachment to extruder
K. Die land
(1)
I
J
F
A
D
C
B
H
G
K
E
A. Die body, crosshead
B. Mandrel, pin, male die part
C. Die, die bushing, female die part
D. Die retaining ring
E. Die retaining bolt
F. Die centering bolt
G. Mandrel holder
H. Air hole
I. Seat for breaker plate
J. Ring for attachment extruder
K. Die land
Material feed
Radius
Water in
Out
Tapered water-cooled mandrel
Insulation
Heater
Offset tubing die with cooled mandrel for sizing

Figure 17.12 Examples of different pipe die inline and crosshead designs

Foam Die

Spider dies are used to a large extent because of their low cost and for many applications in thermoforming, the spider lines can be aligned with edges and center material, which is trimmed and recycled. Spiral dies are used when spider marks are unacceptable. Its center mandrel normally is adjusted to control overall gauge by having tapered exit lips and adjusting the mandrel axially to change the gap.

Profile Die

Solid profiles can be simple flat plate dies with finished land geometry and pre-land dimensions determined by experience and trial in conjunction with sizing plates. If hollow shapes are extruded, supports are necessary, and tubing applications can have inflation air holes. Most of the profile dies, particularly those used in long production runs, require precision dies to meet very close tolerance requirements.

Wire Coating Die

A specialized case of profile extrusion exists when coating wire. The wire is fed through a hardened insert in the center of the die at high speed and the plastic is extruded around it through a manifold or multiple ports. Most dies are subjected to very high internal pressures since the uncommon pressure of over 5,000 psi (35 MPa) is required.

The usual crosshead die has a 90° angle between the wire line and the extruder body axis. Different angles are also used to improve processability. With this setup, the entire length of the extruder projects sideways from the coating lines. To help melt flow from developing dead spots in the melt channels with certain plastics, 30° or 45° crossheads can be used. They provide a more streamlined interior and the extruder location is better adapted to some plant layouts. Regardless of the angle used the process relates to draw ratio balance (DRB) and drawdown ratio (DDR) to ensure proper coating. Plastics have different DRBs and DDRs that can be used as guides to processability and to help establish their various melt characteristics.

Draw Ratio Balance

Target is to set uniformity and balance in the plastic coating. This draw ratio balance (DRB) aids in determining the minimum and maximum values that can be used for different plastics (Figure 17.13).

To determine the DRB the following equation is used where the value of the DRB ranges around one with the ± close to one. Outside the set limits can cause at least out of round and plastic degradation:

$\mathrm{DRB} = (D_D/d_{cw})/(D_T/d_{bw}) \geq 1$ where :
D_D = Diameter of die opening, D_T = Diameter of guide tip,
d_{cw} = diameter of coated wire, and d_{bw} = diameter of bare wire.

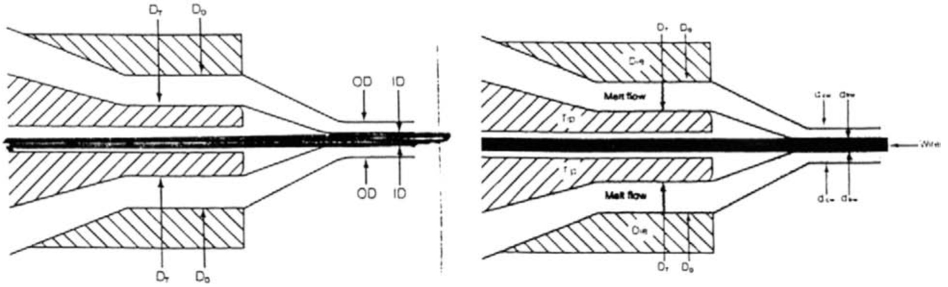


Figure 17.13 (a) Schematic for determining wire coated draw ratio balance in dies.
(b) Schematic for determining wire coated drawdown ratio in dies

Drawdown Ratio

The drawdown ratio (DDR) in a wire die or a circular die, is the ratio of the cross sectional area of the die orifice/opening to the final extruded shape [Figure 17.13(b)].

To determine the DDR the following equation is used:

$$\mathrm{DDR} = (D_D{}^{2}\text{-}D_T{}^{2})/(d_{cw}{}^{2\text{-}d}{}_{bw}{}^{2});$$

With the DDR too high, a rough surface and/or internal stresses in the coating will exist. Typical satisfactory DDR values for LDPE is 1.5, HDPE is 1.2, PVC is 1.5, and nylon is 4.0.

Fiber Die

The spinneret is a type of die principally used in fiber manufacture. It is usually a metal plate with many small holes (or oval, etc.) through which a melt is pulled and/or forced. They enable extrusion of filaments of one denier or less. Conventional spinneret orifices are circular and produce a fiber that is round in cross section. They can contain from about 50 to 110 very small holes. A special characteristic of their design is that the melt in a discharge section of a relatively small area is distributed to a large circle of spinnerets. Because of the smaller distance in the entry region of the distributor, dead spaces are avoided, and the greater distance between the exit orifices makes for easier threading.[143]

Netting and Special Forming Die

The dies are designed to produce different melt flow patterns such as flat to tubular to flat netting types, corrugated flat tubing, perforated tubing, etc.[143] For a circular output, a counter-rotating mandrel and orifice can have semicircular shaped slits through which the melt flow emerges. The slits can be of any shape. If one part of the die is held stationary, then a rhomboid or elongated pattern is formed. If both parts of die rotate, then a true rhombic mesh is formed. During the time when the melt extrudes through the orifice and the slits overlap, a crossing point is formed where the emerging threads appear to be welded but it is a uniform melt flow through the matching/aligned slits. For flat netting, the sliding action is in opposite direction.

Mechanical movement action in a die is used to extrude these different profiles such as tubing or strapping with varying wall thicknesses or perforated wall. It is usually accomplished by converting rotary motion to a linear motion that is used to move or oscillate the mandrel. For certain profiles, such as the perforated tubing, the orifice exit would include a perforated section usually on the mandrel.

Pelletizer Die

With these die-faced pelletizers the extrudate is cut on or near the die face by high-speed knives. There are different designs used that include:

1 An extruder pumps melt through a straining head into the die. It passes through round holes in its die plate where a wet atmosphere exists. Upon exiting the plate, a spinning knife blade cuts the extrudate into pellets. The pellet/water slurry is pumped into a dryer where the pellets separate from the water. Water is reclaimed for repeat use.

2 Very popular are the wet-cut underwater pelletizer. The die face is submerged in a water housing and the pellets are water quenched followed with a drying cycle. Throughput rates are at least up to 50,000 lb/h (22,700 kg/h). Smaller units are economical to operate as low as 500 lb/h (227 kg/h).

3 The water-spray pelletizer, with a rotating knife, uses a water-jet-spray cooling action as pellets are thrown into a water slurry. Throughput is about 100 to 1300 lb/h (45 to 590 kg/h).

4 The hot-cut pelletizer has melt going through a multi-hole die plate. A multi-blade cutter slices the plastic in a dry atmosphere and hurls the pellets away from the die at a high speed. Usually the cutter is mounted above the die so that each blade passes separately across the die face and only one blade at a time contacts the die. Pellets are then air and/or water quenched, followed with drying if water is involved. Throughput is up to at least 15,000 lb/h (6810 kg/h).

5 The water-ring unit has melt extruded through a die plate and cut into pellets by a concentric rotating knife assembly. Pellets are thrown into a rotating ring of water inside a large hood. After cooling in the water, they are spirally conveyed to a water-separated and then to a drying operation.

6 With the rotating-die unit, a rotating hollow die and stationary knife is used. The die, which looks like a hollow slice from a cylinder, has holes on its periphery; melt is fed into the die under minimal pressure and centrifugal force generated by the die rotation causes the melt to extrude through the holes. Pellets cut as each strand passes a stationary knife are flung through a cooling water spray into a drying receiver.

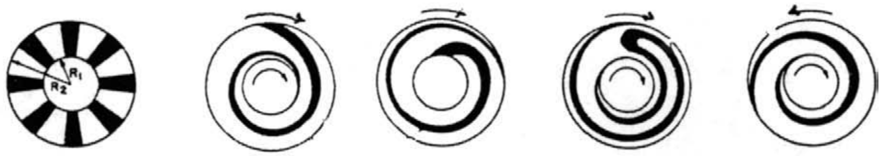
Coextrusion Die

Coextrusion can be performed with flat, tubular, and different shaped dies. The simplest application is to nest mandrels and support them with spiders or supply the plastic through circular manifolds and/or multiple ports. Up to 8-layer spiral mandrel blown film dies have been built that require eight separate spiral flow passages with the attendant problem of structural rigidity, interlayer temperature control, gauge control, and cleaning. Many techniques are available for coextrusion, some of them patented and available under license (Chapter 5).

For flat dies there are basically the feedblock (single manifold) or the adapter (multimanifold) dies with a third system that combines the two basic systems. This third system provides processing alternatives as the complexities of coextrusion increases. The feedblock method combines several monolayer manifolds in a common body creating a multi-manifold feedblock die. Each manifold processes a distinct layer of product until the flows from all manifolds are merged into a single multilayer flow and extruded from a set of common lips. With the single manifold die the plastics meet (combine surface to surface) and spread to a given web width.[143]

There are dies with at least 115 layers of coextruded plastics that have been produced (Chapter 5). Mechanical movement action converting rotary motion to a linear motion is used to move or oscillate the mandrel in a die. Result is to extrude different profiles such as tubing or strapping with varying wall thicknesses or perforated wall. This Dow patented process generates hundreds of layers, each one thinner than the wavelength of light.[206] The tubing die generates a large number of layers by rotation of annular die boundaries.

It can be accomplished by a novel coextruded blown film (or flat film) die. Product produces iridescent effects simply by taking advantage of some basic optical principles. Alternating layers of two plastics, such as PE and PP, with at least 115 (and many more) produce an extruded film 0.5mil (0.013 mm) thick. Individual plastic components are forced through a feedport system into a die in alternating layers extending radially across the annular gap [Figure 17.14). Simultaneously rotation of the dies inner mandrel and outer ring, deform the layers into long thin spirals around the annulus.



A. Feed distribution entering annular die
B. Case 1
C. Case 2
D. Case 3
E. Case 4

Figure 17.14 Examples of layer plastics based on four modes of die rotation

The increased interfacial surface area related to rotational speed multiplies the number of layers. Overall the number of layers and layer thickness is determined by the dimensions of the annulus, the number of feed ports for each phase, the extrusion rate, and the rotational speed of the die mandrel and ring relative to the feed ports. The resulting four basic layer patterns are generated by four modes of the die rotation. Case 1 has the inner die mandrel rotating while the outer ring is stationary where layers are thicker near the outer ring. Case 2 has the inner die mandrel stationary while the outer ring rotates with layers thinner near the outer ring. In Case 3 both inner and outer die members rotate at the same speed and direction; the result is that layers of curved open-end loops and thicker layers are in the center. Case 4 has inner and outer die members counter-rotating at equal speed generating the maximum number of symmetrical layers with the thickest in the center. All these examples have layers that are concentric. The deformation is usually so large that the spiral characteristic is indistinguishable when examining the extrudate in the cross section.

Computer

The use of computers has become part of the lifeline in producing dies and other tools and products via its displays and/or developing physical prototypes. Creating physical models can be time-consuming and provide limited evaluation, however they can be less expensive. By employing kinematic (branch of dynamics that deals with aspects of motion apart from considerations of mass and force) and dynamic analyses on a design within the computer, time is saved and often the result of the analysis is more useful than experimental results from physical prototypes. Physical prototyping often requires a great deal of manual work, not only to create the parts of the model, but also to assemble them and apply the instrumentation needed as well.

CAD (computer-aided design) prototyping uses kinematic and dynamic analytical methods to perform many of the same tests on a model. The inherent advantage of CAD prototyping is that it allows the engineer to fine-tune the design before a physical prototype is created. When the prototype is eventually fabricated, the designer is likely to have better information with which to actually create and test the prototype model.

Engineers perform kinematic and dynamic analyses on a CAD prototype because a well-designed simulation leads to information that can be used to modify design parameters and characteristics that might not have otherwise been considered.[1] Kinematic and dynamic analysis methods apply the laws of physics to a computerized model in order to analyze the motions within the system and evaluate the overall interaction and performance of the system as a whole. It allows the engineer to overload forces on the model as well as change location of the forces. Because the model can be reconstructed in an instant, the engineer can take advantage of the destructive testing data. Physical prototypes would have to be fabricated and reconstructed every time the test was repeated. There are situations in which physical prototypes must be constructed, but those situations can often be made more efficient and informative by the application of CAD prototyping analyses.

CAD prototyping employs computer-aided testing (CAT) so that progressive design changes can be incorporated quickly and efficiently into the prototype model. Tests can be performed on the system or its parts in a way that might not be possible in a laboratory setting. It can also apply forces to the design that would be impossible to apply in the laboratory.[332–334]

Tooling and prototyping

Rapid tooling (mold and die) and product rapid prototyping provides reducing development cycles. Rapid tooling (RT) and rapid prototyping (RP) is any method or technology that enables one to produce a tool or product quickly. The term rapid tooling refers to RT-driven tooling. A prototype is a 3-D model suitable for use in the preliminary testing and evaluation of a mold, die or product. It provides a means to evaluate the tool's or product's processing performances before going into production. The ideal situation is for the prototype to be the actual tool made in production. However, techniques such as machining stock material to using RT or RP methods, can make prototypes for preliminary or final evaluation prior to manufacturing the tool or product.[336]

The technology of RT and RP provides a quick way timewise between design creativity ideas and the fabricated product. More precision tooling and prototype materials continue to become available with system speeds keep increasing. The plastics and other industries are actively engaged in using these rapid systems. As an example the USA international space agencies are experimenting with RP to quickly replace parts in space vehicles.[337]

Various methods are used. Two prime groups exist that are identified as indirect (or transfer) and direct. The indirect methods involve the use of a master pattern from which the tool is produced. Reduction in time to produce tools, repeatability, meeting tight dimensions, and other factors influence the use of direct methods. Ultimately, companies want to produce the molds directly, although most of the direct tooling methods are not without limitations. Many different companies worldwide are actively pursuing RT approaches and eliminating or decreasing limitations.

Indirect tooling methods are many. Examples include cast aluminum, investment metal cast, cast plastics, cast kirksite, sprayed steel, spin-castings, plaster casting, electroforming, room temperature vulcanizing (RTV) silicone elastomer (Chapter 2 Silicone Elastomer), elastomer/rubber, reaction injection, stereolithography,[338–344] (Table 17.4), direct metal laser sintering, and laminate construction.

Table 17.4 Rapid prototyping processes

Manufacturer	Process name	Material & structure generation
3D Systems Inc., Valencia, CA, U.S.A.	Stereo lithography Apparatus (SLA)	Photopolymer system; point-by-point irradiation with a HeCd resp. an argon ion laser
CMET, Japan	Solid Object UV Plotter (SOUP)	Photopolymer system; point-by-point irradiation with an argon ion laser
SONY-Japan Synthetic Rubber, Tokyo, Japan	Solid Creater	Photopolymer system; point-by-point irradiation with an argon ion laser
SPARX, Molndal, Sweden	Hot Plot	Self-adhesive film; cutting of the films layer by layer with a thermal electrode
Stratasys Inc., Minneapolis, WI, U.S.A.	Fused Deposition Modelling (FDM)	Thermoplastic filaments (PA, etc.)as well as wax; melting the plastic in a mini extruder
Light Sculpting Inc., Milwaukee, WI, U.S.A.	LSI	Photopolymer system; irradiation of the entire surface with a UV lamp
Mitsui Engr' & Shipbuilding Ltd., Tokyo, Japan	COLAMM	Photopolymer system; point-by-point irradiation with a HeCd laser

18 AUXILIARY EQUIPMENT

Introduction

Within the plastics industry an important part is the machinery auxiliary sector also called secondary sector. To provide the millions of plastic products used worldwide many different fabricating lines are used. These lines have primary and auxiliary equipment. Primary equipment refers to the machine that fabricates a product such as an injection molding machine, extruder, blow molder, thermoformer, etc. (Chapters 4 to 17). Auxiliary equipment (AE) supports the primary equipment. This type equipment is required in order to produce products that fit into the overall manufacturing cycle. There are many different types supporting non-automated to automated upstream and downstream production in-line or off-line systems maximizing the overall processing efficiency of productivity and reducing operating cost. Examples of this equipment have been reviewed throughout this book. This chapter provides an overview to this very large market (Figures 18.1 and 18.2).[345–351]

A few of the many AE are accumulator, assembly, blender, bonding, chemical etching chiller, cooling, computer, flash remover, conveyer, cutter, decorating, dicer, die heater, dryer, dust recovery, engraving, fabricating, fastening, feeding, finishing, gauging, granulator,[470] grinder, heater, instrumentation, joining, knitting, labeling, leak detector, loading, machining, material handling, measuring, metering, mixer, mold extractor, mold heat/chiller, monitoring, part handling, pelletizer, plating, polishing, primary machine component, printing, process control for individual or complete line, pulverizing, purging, quick mold or die changer, recycling system, robotic handler,[177] router, saw, scrap reclaimed, screen changer, screw/barrel backup, sealing, separator, sensor/monitor control, shredder, software, solvent recovery,

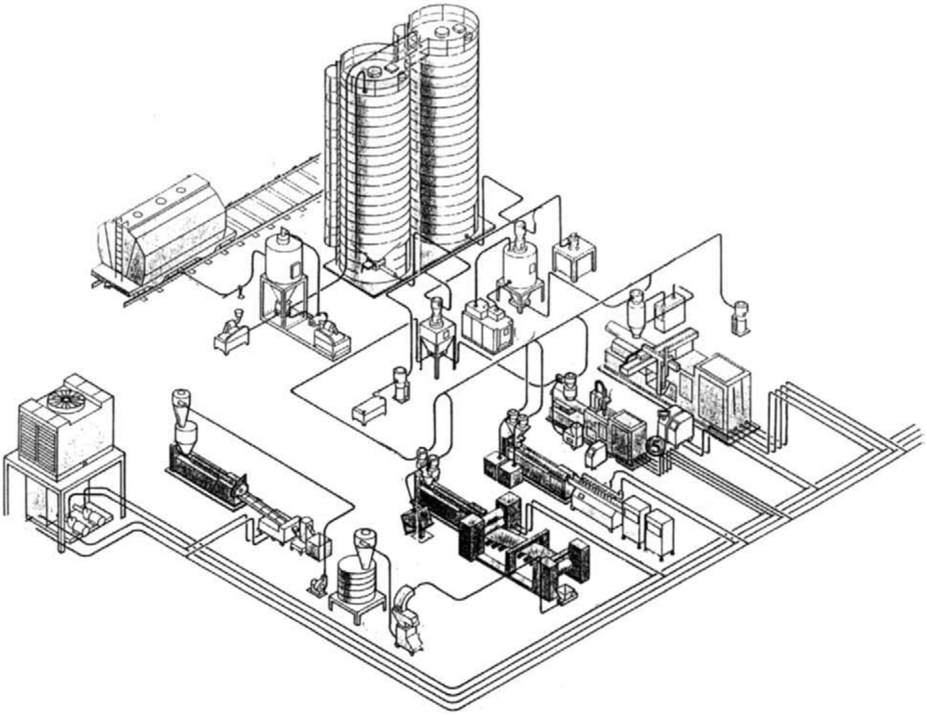


Figure 18.1 Examples of plant layout with extrusion and injection molding primary and auxiliary equipment

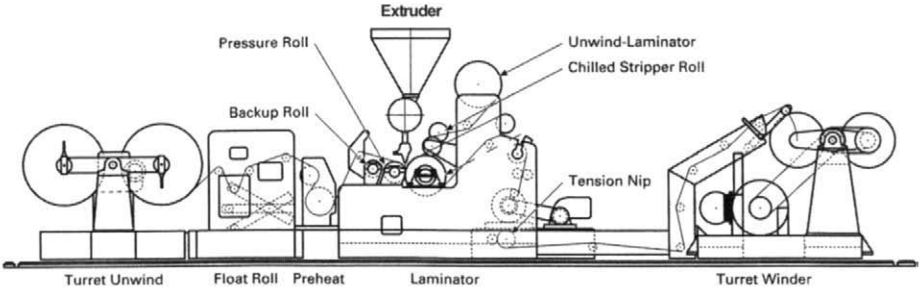

Extruder
Pressure Roll
Unwind-Laminator
Chilled Stripper Roll
Backup Roll
Tension Nip
Turret Unwind
Float Roll
Preheat
Laminator
Turret Winder

Figure 18.2 Example of an extrusion laminator with auxiliary equipment

solvent treater, statistical process controller, statistical quality controller, storage, take-off equipment, testing equipment, trimmer, vacuum debulking, vacuum storage, water-jet cutting, welding, and others.

AE can sometimes cost more than the primary equipment. It is important to properly determine requirements and ensure that the AE interface into the line (size, capacity, speed, etc.) otherwise many costly problems can develop. They have become more energy-efficient, reliable, and cost-effective. The application of microprocessor- and computer-compatible controls that can communicate with the line (train) results in pinpoint control of the line. A set of rules have been developed and used by equipment manufacturers that help govern the communication protocol and transfer of data between primary and auxiliary equipment.

Ideally, fabricating thermoplastic (TP) or thermoset (TS) plastic products will be finished as processed. For example almost any type of texture, surface finish, or insert can be fabricated into the product, as can almost any geometric shape, hole, or projection. There are situations, however, where it is not possible, practical, or economical to have every feature in the finished product. Typical examples where machining might be required are certain undercuts, complicated side coring, or places where parting line or weld line irregularity is unacceptable. Another common machining/finishing operation with plastics is the removal of the remnant of the flash, sprue and/or gate if it is in an appearance area or critical tolerance region of the part.

These secondary operations can occur in-line or off-line. They include any one or a combination of operations such as machining, annealing (to relieve or remove residual stresses and strains), post-curing (to improve performance), plating, joining and assembling (adhesive, ultrasonic welding, vibration welding, heat welding, etc.), cutting, finishing, polishing, labeling, and decorating/printing. The type of operation to be used depends on the type plastic used. As an example with decorating or bonding, certain plastics can be easily handled while others require special surface treatments to produce acceptable products.

Heat sealing is usually applied to the joining of pliable plastics sheet (less than 50 mils thick) and is limited to use on thermoplastic materials. The heat may be provided by thermal, electrical, or sonic energy. A wide variety of heat sealing systems are available.

Plastic sections, which are too thick to be heat-sealed, may usually be welded. There are three major methods in commercial use; heat, solvent, and ultrasonic. In general, these methods are limited to use with thermoplastic materials. These welding techniques have done much to lower the total cost of using plastics in the construction and other industries.

In addition to the various welding techniques, adhesives may join plastic parts. Both thermoplastic and thermosetting resins may be bonded and parts made of different resins are often treated in this manner. There is a wide range of suitable adhesive materials including various monomers, solvents, and epoxies that are in general commercial use. The exact material chosen will be a function of the plastic materials to be joined and the environmental and end use conditions to which the finished part will be subjected.

The increasing use of plastics as construction materials has led to a renewed interest in decorative finishes for plastic products. There are a wide variety of secondary operations that can be used for adding decoration to molded parts. Progress is also being made in providing decorative surfaces in the mold itself. The first use of this is in wood-like panels for wall decoration and furniture parts such as cabinet doors.

Plastics may be printed upon, painted by a variety of processes, wood-grained by essentially a printing process, electroplated, metallized, and hot stamped with gold or silver leaf. Plastic film and sheeting are generally printed or embossed in order to get decorative surfaces. Printing is also used in the mass production of such plastic articles as labels, signs, and advertising displays.

There has been increasing interest in the process of electro-plating plastics. Plating can produce chromelike, brass, silver, gold, or copper surfaces in both smooth and textured forms. There are several systems available commercially for plating plastic materials. In the case of certain plastics such as electroplated ABS, it can be surface-treated chemically to promote bonding of the metals in subsequent steps.

This action eliminates the need for a costly mechanical roughening process that most other materials require. The depositing of a metal surface on plastic parts can increase environmental resistance of the part, also its mechanical properties and appearance. As an example a plated ABS part (total thickness of plate 0.015 in.) exhibited a 16% increase in tensile strength, a 100% increase in tensile modulus, a 200% increase in flexural modulus, a 30% increase in Izod impact strength, and a 12% increase in deflection temperature. Tests on outdoor aged samples showed complete retention of physical properties after six months.

It is possible for plated plastics to corrode if the metal coating is not properly applied or if it is damaged in such a way as to allow electrolytic interaction in the plating layers. However, the plastic substrate will not corrode itself, nor will it contribute to further corrosion of the plating layers. In general, plated plastics will fare better than metals when exposed to corrosive environments.

Material/product handling

Design of the raw material and fabricated product handling system has a major impact on the plant's manufacturing costs and housekeeping. It is based on the different materials used, annual volume of each material, number of different colors, production run lengths, etc. A properly designed pneumatic system generates plastic velocities of at least 5000 ft/min (1500 m/min).

Material handling can start with delivery of bulk plastic to the plant that can be by trucks or rail cars. Trucks typically carry 1,250 ft^3 (36 m^3) of material. Most often the truck has a positive displacement-pumping unit or the user supplies a pressure system to the silos. Rail cars can store up to 5,200 ft^3 (148 m^3) in 4 or 5 compartments with user providing unloading systems to the silos. Unloading costs are largely determined by the throughput required.

Plastics may be supplied in different quantities. There are drums [from 15 lb (6.8 kg)], bags [50 lb (23 kg)], gaylords [cardboard box usually lined with plastic sheet holding 1,000 lb (454 kg)], or bulk fabric sack bags [also called super sacks, super bags, or jumbo bags holding 2,000 lb (908 kg)] that bulk because of low volume usage, costs, moisture situation, etc. To move materials from these containers systems rquires: vacuum tube conveyors, dumper and pressure unloader, or fork truck hoist, etc. Plastic storage box containers are also used rather than bags or drums. Box sizes and weights vary and conform to a standard size pallet on which they are shipped and moved in the plant.

Bulk density of material influences solids conveying and processing plastic. It is the weight of a unit volume of the material including the air voids. The actual material density is defined as the weight of unit volume of the plastic, excluding the air voids.

If the bulk density is more than 50% of the actual density, the bulk material likely will be reasonably easy to convey in a material handling system and through a plasticator (Chapter 3). With bulk density less than 50% of the actual density, then solids conveying problems are likely to occur in a material handling system and through a plasticator. When the bulk density becomes less than 30% of the actual density, a conventional plasticator usually cannot handle the bulk material. Such materials may require special feeding devices, such as crammer feeders or special extruder design, for example a large-diameter feed section tapering down to a smaller diameter metering section.

Different methods are used to move plastic that range from manual methods to full automation for raw material to fabricated parts. Use includes automatic bulk systems, in-line granulators, parts removal robots, conveyors, stackers or orienters, etc. The equipment chosen must match the productivity requirement of the line.

When conveying plastics a properly designed system is to take the shortest distance. The shortest distance between two points is a straight line. The maximum conveying distance is usually 800 equivalent ft (244 m). A gradual upward slope is never better than a vertical lift. When the plastic passes through a 45° or 60° elbow, it ricochets back and forth creating turbulence that destroys its momentum.

With vacuum/pressure the conveying action provides double the conveying rates of vacuum alone. Plastic lines are not recommended for conveying lines since static electricity will be generated and will interfere with the movement of plastics. A rather simple and useful test to determine if material is going to be difficult to convey can be used. Take a handful of the plastic and squeeze it firmly. Upon opening your hand, if the lines in your palm are filled with fines, it will be difficult.

Fines are very small particles, usually under 200 mesh, accompanying larger forms of powders. When plastics are extruded and pelletized, varying amounts of oversized pellets and strands are produced, along with fines. When the plastics are dewatered/dried or pneumatically conveyed, more fines, fluff, and streamers may be generated. They can develop when granulating plastics. Usually they are detrimental during processing so they are removed or action is taken to eliminate the problem during pelletizing, grinding scrap, etc.

In addition to conveying plastic, there is a wide variety of tasks for warehousing such as storing raw materials, additives, auxiliary equipment, spare parts, molds, dies, tools, processed plastic parts, etc. They require handling and storage procedures that are logged economically. Various systems are used successfully such as the unit warehouse that makes use of pallets, cages, and similar equipment. It employs a certain organizational scheme for integrating order picking and transportation. The system is perfected by integration of the inward and outward flow (input-output matrix) of goods, the factory administration, process control, quality control, etc.

Various properties and characteristics of materials used in the plastics industry that can be conveyed pneumatically affect the sizing and design of the conveying system. As an example the specific gravity is an aid in determining how much airflow is needed to lift a particle in an air stream. Particle size is also a consideration in pneumatic conveying systems. The material has to be tested to determine the amount of fines and dust that may be contained in the material. This will help determine the type of airflow in a system, whether it is a vacuum or pressure system, along with the type of filters that will be utilized in the system. Particle size is measured by using sieves that are made to standards set by the American Society of Testing Materials of the U.S. Standards Institute.

The melting point of a material should be determined. There are plastic materials that melt at low temperatures. If these materials are conveyed at a faster rate than necessary, they may slide against the walls of the conveying tubes or, more commonly, collect in a bend, and heat up by friction, which in turn will cause them to begin to melt, producing what is called angel hair. This thin plastic will partially peel away from the wall as the pellet moves back toward the center of the air stream, leaving what appears to be a fine hair. If enough of this occurs with other pellets in a particular area in a system, the angel hair will clog the system, thus preventing material from flowing.

Materials that are abrasive may cause the conveying tubes to wear through quickly. Abrasive materials may have to be conveyed through-resistant material or at a lower rate than other materials.

Very few plastics have a corrosive characteristic that may contain acids and erode tubing. An acid content test can be conducted by determining their pH factor. A pH of 7 is neutral. Any reading below 7 is an indication of acid. A pH reading above 7 would indicate that the material is alkaline. Powdered materials with strong acid indications will have to be conveyed through special pneumatic systems in order to prevent any corrosion from taking place within the system.

Control feeding devices to the hopper of primary equipment (injection molding, extrusion, etc.) is important to provide products that meet performance requirements at the lowest cost. Equipment manufacturers have increased the feeding accuracy using different devices such as microprocessor blender/mixer controllers. Also materials are being reduced in size with more uniformity to significantly improve uniformity in melt. Processors can use blenders and other devices mounted on hoppers that target for precise and even distribution of materials.

Hoppers are receptacles on the machines which direct the plastic materials (pellets, granules, flakes, etc.) being fed into the plasticators. The hopper can be fitted with devices to perform different functions. As an example they can be fitted with a hinged or tightly fitted sliding cover and a magnetic screen for protection against moisture pick-up and metal ingress. It is usually advisable to install a hopper drier, especially when processing certain materials such as hygroscopic plastics, regrind, and colors.[352, 353] It can be of value in limiting material handling, as well as removing moisture.

There are different equipment designs used for dispensing, metering, and mixing that use volume and the more popular/useful/cost saving gravimeter/weight blenders located over the feed hopper. Included can be motor-driven augers and vibrators as well as air-driven valves to process materials such as flakes, powders, granular material, liquids, and pellets.

Plastic usage for a given process should be measured so as to determine how much plastic should be loaded into the hopper. The hopper should hold enough plastic for possibly ½ to 1 hour's production. This action is taken so as to prevent storage in the hopper for any length of time.

Processing TPs when compared to TS plastics is relatively easy. Free-flowing TS molding compounds in pellet forms based on plastics such as phenolic, melamine, or urea can be metered from a hopper just like TP pellets. However doughy-bulk TS polyester and vinyl ester compounds, such as bulk molding compound (BMC), require force-feeding. There are basically two ways of feeding these materials to the plastication unit, namely, the batchwise stuffer screw or continuous screw stuffer techniques. These types of materials are principally used in injection molding machines.

Different methods for handling and moving molded products are used. The type employed depends on factors such as the fabricating equipment being used, size and shape of products, setting up for secondary operations, quantity of products, system for warehousing, and system for packaging and shipping to a customer. Automating products/parts removal and other downstream operations reduces processing costs and increases profitability. Automatic parts handling devices can be divided into two categories: the take-out with transfer mechanism or gravity systems that receive ejected parts from a mold and robots that perform machine tending and a variety of downstream handling tasks.

Robots replicate in various degrees the actions of the human arm and hand. When used for parts removal, they reach into the mold, grasp parts, remove parts and runners from the mold, and transfer them to the next stage of downstream operations. For simple applications such as machine tending, plastics processors use non-servo robots, in which positioning and speed are controlled mechanically and sequence of movement is determined by a robot controller. For more complex downstream functions such as sophisticated parts orientation, secondary trimming, hot stamping, packaging, etc., they use full servo robots, in which position, speed, and sequence are computer-controlled with a feedback closed loop.

Quick and efficient approach is used to move and handle molds, dies, plasticators, and other parts of the production line equipment. To save valuable time and particularly machine downtime, quick changes with microprocessor control are used in certain plants replacing manual mold changes.

Figure 18.3 is an extrusion line schematic drawing of tension control equipment for the unwinding substrate. The arrows indicate the motions of the driven tension control rolls and idlers as well as the substrate, and the direction of outward pressure-on the rolls. Figure 18.4 is what is called a flying splice on a double-station-unrolling stand where:

1 In the starting position, the substrate is fed into the coater from the old roll A over a bumper roll.

2 The old roll A that will soon be fully unrolled is moved forward, and a new roll B moves onto the stand where the old roll was before.

3 Adhesive is applied along roll B near the beginning of the substrate web. The driving rings are moved, located below roll B, against the roll that starts revolving until it has reached the required surface speed.

4 Roll B is moved forward until it contacts the bumper roll. Since now both rolls A and B rotate, substrate from both rolls is bonded together.

For a very short time, the double substrate layer is fed into the coater. The moment the substrate from roll B has caught on, a cut-off knife immediately moves into position against the substrate. In the meantime, the driving rings are removed away from roll B. All the steps described under d must occur almost simultaneously, taking no more than a few seconds.

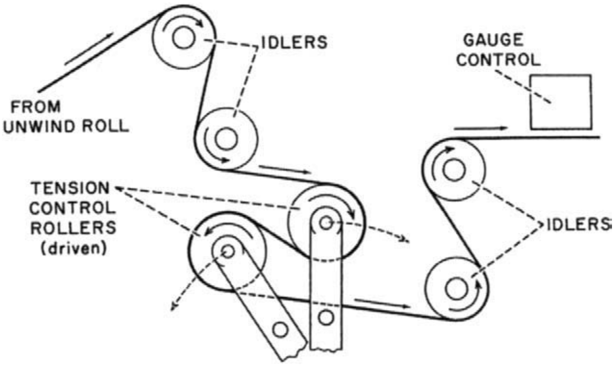


Figure 18.3 Examples of tension control rollers in a film, sheet, or coating line

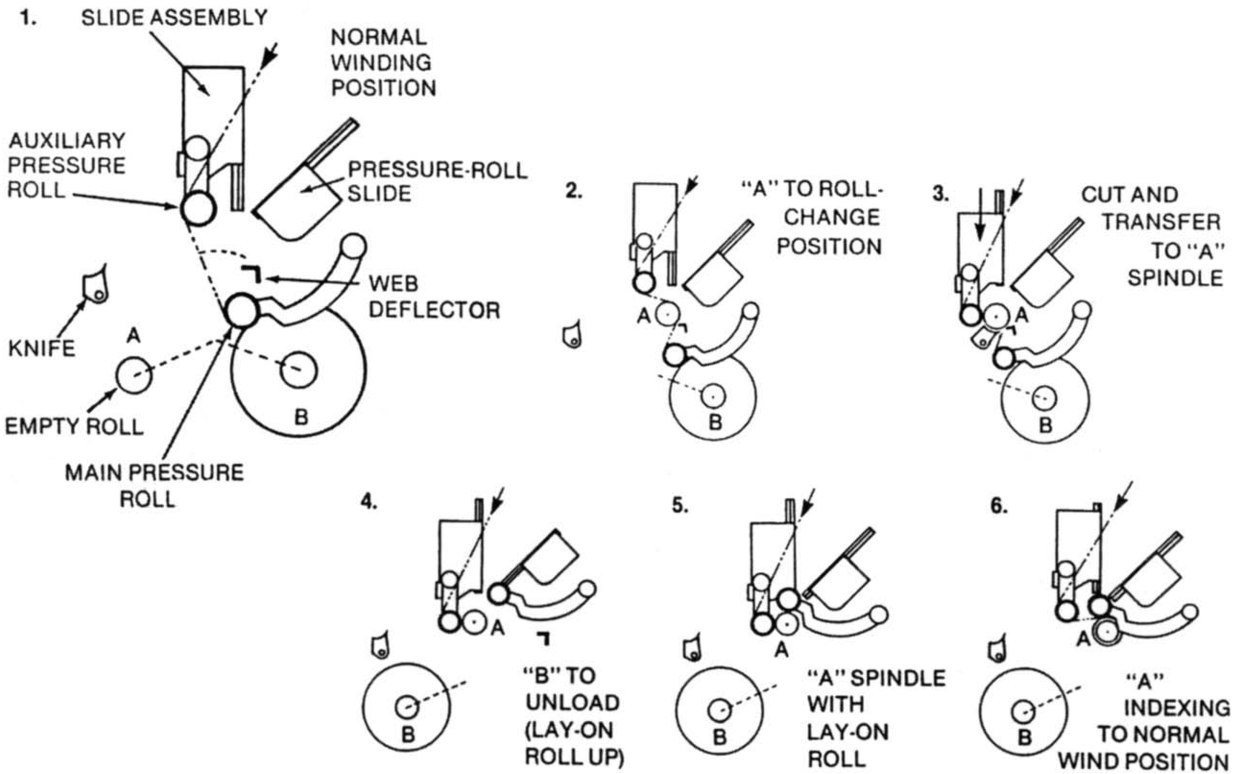

1.
SLIDE ASSEMBLY
NORMAL WINDING POSITION
AUXILIARY PRESSURE ROLL
PRESSURE-ROLL SLIDE
WEB DEFLECTOR
KNIFE
A
EMPTY ROLL
B
MAIN PRESSURE ROLL
2.
"A" TO ROLL-CHANGE POSITION
A
B
3.
CUT AND TRANSFER TO "A" SPINDLE
A
B
4.
A
B
"B" TO UNLOAD (LAY-ON ROLL UP)
5.
A
B
"A" SPINDLE WITH LAY-ON ROLL
6.
A
B
"A" INDEXING TO NORMAL WIND POSITION

Figure 18.4 Example of roll-change sequence winder (courtesy of Black Clawson)

There are many hundreds of different winders and rolls used in extrusion film and sheet lines. There are those used for adhesive bonding, ultrasonically sealing a decorative pattern, reducing wrinkles of web using a herringbone idler roll, matted and unmated embossing rolls, dancer roll controlling web tension, turret wind-up reel change system, sheet roll stock winder with triple fixed shafts, blown film line going through control rolls and dual wind-up turrets, and so on.

Throughputs of winders can be over 2,200 lb/h (1,000 kg/h). Transfers from one roll to another can take less then a second. Material speeds are up to at least 2,200 ft/min in cast film lines; at least 999 ft/min in blown film lines. Blown film lines may want to use reverse winding systems to allow coextruded films to be wound with a particular material as the inside or outside layer.

Their weights can be very low to at least 16,000 lb. Diameters are at least up to 60 in. and widths at least up to 30 ft. Some rolls require roundness and surface finishes to be within 0.00005 in. (0.00127 mm). Many winders offer sophisticated features and are highly automated, but some are designed to answer the need for simplicity, versatility, and economy. There are surface winders with gap-winding ability for processing tacky films such as EVAs (ethylene vinyl alcohols) and the metallocene plastics. Information on these different types of rolls is provided in Table 18.1.

Decorating

An important area in fabricating products is the finishing or decorating of plastics. It is usually performed during fabrication or can be performed after fabrication. Included are many different methods of adding either decorative and/or functional surface effects such as printed information to a plastic product. Plastics, of course, are unique in that color and decorative effects can be added to plastics prior to and during manufacturing. Pigments and dyes, for example, are compounded into the plastic before they are processed so that color is part of a plastic product and can be continuous throughout the product or just on the surface.

Plastic parts can be post-finished in a number of ways. Film and sheet can be post-embossed with textures and letterpress, gravure, or silk screening can print them. Rigid plastic molded parts can be painted or they can be given a metallic surface by such techniques as metallizing, barrel plating, or electroplating. Another popular method is hot stamping in which heat, pressure, and dwell time are used to transfer color or design from a carrier film to the plastic part. Popular is the in-mold decorating that involves the incorporation of a printed foil into a plastic part during molding so that it becomes an integral part of the piece and is actually inside the piece under the surface. There are applications, such as with blow molded products, where the foil provides structural integrity thus reducing the more costly amount of plastic to be used in the products.

Many plastic products are decorated to make them multi-colored, add distinctive logos, or allow them to imitate wood, metal and other materials. Some plastic products are painted since their as-molded appearance is not satisfactory, as may be the case with reinforced, filled, or foamed plastics.

Common decorative finishes applied to plastic are spray painting, vacuum metallizing, hot stamping, silk screening, metal plating, sputter plating, flame spray/arc spray, electroplating, printing and the application of self-adhesive label, sublimation printing, decal, and border stripping. In some cases, the finish will give the product-added protection from heat, ultraviolet radiation, chemicals, scratching or abrasion.

Joining and assembling

Plastic parts can be joined or assembled to other plastic parts of similar or dissimilar plastic materials as well as other materials such as metals. It may be necessary when:

1 the finished assembly is too complex or large to fabricate in one piece, or

2 disassembly and re-assembly is necessary, for cost reduction, or

3 when different materials must be used within the finished assembly.

The ideal situation continues to be in joining or assembling during fabrication whenever it can be done to significantly reduce time and cost of the composite product. When joining and assembling during secondary operations and during fabrication different factors have to be considered such as coefficient of expansions of the different materials.

Different processes are used for joining and assembling different parts that include adhesives, solvents, mechanical, and welding.[2, 41, 354–359]

Adhesive bonding often is the most efficient, economical, and durable method for plastic assembly. The adhesive can cover the entire bond

Table 18.1 Examples of different rolls used in different extrusion processes

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Tension Control Roll These type rolls provide the important function of material tension control. There is a proportional relationship between winding tension and lay-on-roll forces (eliminating areas were bumps, valleys, unwanted stretch, etc. develop). There are various tension control techniques available. The proper selection involves decisions on how to produce the tension, how to sense the tension, and how to control the tension. For instance, if the material has a very low tension requirement and if exact control is required, then perhaps, using a magnetic particle brake with an electrical transducer roll with appropriate electronic control is best. However, if the material is on large diameter rolls and moves at slow speed, then a roll follower system can be used effectively.

Dancer Roll These can be used as a tension-sensing device in film, sheet, and coating (wire, film, etc.) lines. They provide an even controlled rate of material movement. Type roll can have an influence on the roll's performance. As an example, chrome plated steel casting drums would seem to be very durable dancers. If used in the absence of a nip roll, should last many years. However, these rolls are in fact very soft due to the annealing which good rolls receive for stress relieving the steel.

As an example a casting drum can been coupled with a steel chill roll to nip polish a cast film web. The casting drum was imprinted by hard plastic edges or die drips. This action occurs because the compressive stresses in a solid plastic passing through the nip of the rolls will exceed the yield strength of the relatively soft steel drum surface. Higher line speeds make the problem worse. In order to prevent this damage, the roll must be hardened.

Adjustable Roll The dancer rolls, canvas drag brakes, various pony brakes, and pneumatically operated brakes are manual adjustment systems. The most expensive would be the regenerative drive systems. The transducer rolls and dancer rolls would be a close second. These systems are usually required in high web speed applications where accurate tension control of expensive and/or sensitive material is paramount. With roll windup systems different roll or reel-change systems are used to keep the lines running at their constant high speeds.

Decorating Roll When the melt leaves the die and enters roll nips, it is soft enough to take the finish of the rolls it contacts. Thus, in addition to smooth and highly glossy finishes, textured or grain rolls can be used. They can impart a mirror image. They can give both functional and aesthetic qualities to the film or sheet. There are as many different grains as the imagination can conjure up.

Cooling Roll These systems range from very inexpensive with rather poor surface non-uniform temperature control to the usually more desirable (and expensive) rolls suitably cored to permit controlled circulation of heat generated by the pumps. For example, a 20 hp water pump can require up to 4 tons of additional chilling capacity to remove the heat generated by the pump.

Spreader/Expander Roll These are bowed rolls that stretch film to remove wrinkles. They create an ever-increasing skew or angle on the roller's rotation, providing a shift in web direction from the roll's center outwards toward the ends. Its major benefit is that the roller "crown" or skew can be adjusted while the line is running to shift the orientation of the web as it passes over the roller. However, the bowed roller design can alter the natural flow of the web, creating uneven tension across the face of the roller, resulting in possible drag in the processing line. This action can cause the web to stretch and distort, especially with thin films. They require a specific amount of space to provide optimum performance.

These grooved rolls have opposing, etched spiral grooves that start at the roll's center and spiral toward the ends. As the roll turns, air flows and follows the direction of the grooves along the metal surface moving from the center of the roll outward. This action forces any web wrinkles out towards the ends of the roll. The expander film spreader roller can consist of a flexible center shaft, a series of bearings placed along the shaft, a flexible metal inner covering, and a smooth-surfaced, one-piece elastomer outer covering.

There is the stretchable one-piece rubber sleeve supported by a series of brushes. As the roll rotates, the entire roller sleeve, as opposed to individual cords, expands and contracts to provide spreading action. The two factors of the wrap or angle at which the web enters onto the roller and the angular displacement of the end caps control the amount of spreading. Notable advancements in this expandable sleeve roller include a smooth, continuous surface that does not produce marking or allow air to enter under the web. Unfortunately the stretching of the rubber can cause the roller to eventually wear over time.

Winding Strain Roll Winding strain can occur at the end of the line. It is the phenomena of a wound roll of film turning into hard rock corrugated nightmare in a few days. This action is caused by several factors: (1) Trapped air as the roll is being wound makes a roll feel soft. Static charges helps trap air. Lay-on roll help to squeeze air out but can also create other problems. The rapid escape of air can produce telescoping. (2) Tension creates a compression load, which will squeeze out the very thin film of air, crush under-layers, and crush cores. Tension also tends to even out some of the wrinkles and irregularities. (3) Room temperature recoverable strains are residual processing strains that will release themselves at room temperature to produce a stress and/or shrinkage. Available are techniques for predicting the level of room temperature recoverable strains. (4) Crystallization of crystalline plastics also produces shrinkage of a magnitude generally ½ to 2%. Crystals take less space and thus, as the crystal structure goes to completion, shrinkage occurs. It is permitted to shrink for about one to two days, slit, and rewound.

Preheater Roll As an example in a coating line a heated roll is installed between a pressure roll and unwind roll. Purpose is to heat the substrate prior to being coated.

area and thus can spread stresses rather than concentrating them at the point of fastener attachment. No bosses or holes are required for an assembly that is more aesthetically pleasing. This stress diffusion can also lead to the use of thinner and lighter-weight sections. Certain considerations must be taken into account to insure that the adhesive bond will be adequate for the final product. Some adhesives may attack or craze plastics and these adhesives should be eliminated early in testing.[357]

Use is made of different types of mechanical fasteners that include screws and nuts, bolts, washers, snap-fits, self-tapping screws, thread-forming screws, thread-cutting screws, inserts, molding inserts, press fits, and staking (hot, cold). They provide simple and versatile joining methods. Mechanical fasteners are made from plastics, metals, or their combination. Includes use of fasteners that can be removed and replaced or reused when servicing of the part is necessary. Screws, nuts, and inserts can be made of plastic or metal. In certain molded assemblies threads are molded in plastic that in turn use screws for joining.

Different heat softening methods are used to weld different thermoplastic-to-thermoplastic. Different processes are used to make permanent bonds between materials that can meet requirements such as shapes, thickness, appearance, bond strength, capability of different being bonded, hermetic seal, or effect of additives or fillers used in the plastics. Once a process is being used, recognize that if the compound additives or fillers are changed or added, bond performance can change or even not exist. As an example with a certain amount of glass fiber fillers (they do not melt) action in welding can disappear.

The welding processes used include hot plate welding, laser welding, hot gas welding, infrared welding, vibration welding, spin welding, ultrasonic welding, induction welding, radio frequency welding, microwave welding, resistance welding, and extrusion welding.[447, 448, 476]

Machining

Although most plastic parts are usually fabricated into their final shape, there are parts that require secondary machining operations (cutting extruded shape. cutting molded gates, cutting thermoformed scrap, etc.). Stock plastics such as blocks of plastics, rods, etc. are machined.[306, 360-370] Different machining operations arc involved: milling, drilling, cutting, finishing, etc. (Table 18.2). Different reasons exist for machining such as:

1 Dimensions of fabricated parts may not be sufficiently accurate. Extreme accuracy. particularly when using certain processes or machines with limited capabilities can be expensive to achieve.

2 Fabricated parts can be relatively expensive in small-scale production. It may also be desirable to make parts by machining when the production is not large enough to justify the investment in fabricating equipment (mold, die, etc.).

3 Supplementary machining procedures may be required in finishing operations.

Table 18.2 Examples of machining

Machining method	Purpose of machining operation
Cutting	
with a single-point tool	Turning, planing, shaping
with a multiple-point tool	Milling, drilling, reaming, threading, engraving
Cutting off	
with a saw	Hack sawing, band sawing, circular sawing
by the aid of abrasives	Bonded abrasives: abrasive cutting off, diamond cutting off Loose abrasives: blasting, ultrasonic cutting off
shearing	Shearing, nibbling
by the aid of heat	Friction cutting off, electrical heated wire cutting off
Finishing	
by the aid of abrasives	Bonded abrasives: grinding, abrasive belt grinding Loose abrasives: barreling, blasting, buffing

Types of parts	Kinds of machining methods used
Bearing, roller	Turning, milling, drilling, shaping
Button	Turning, drilling
Cam	Turning, copy turning
Dial and scale	Engraving, sand blasting
Gear	Turning, milling, gear shaving, broaching
Liner and brake lining	Cutting off, shaping, planing, milling
Pipe and rod	Cutting off, turning, threading
Plate (ceiling, panel)	Cutting off, drilling, tapping
Tape (mainly for PTFE)	Peeling

Processing method	Purpose of machining operation	Types of machining used
Compression, transfer, injection and blow molding	Degating, deflashing, polishing	Cutting off, buffing, tumbling, filing, sanding
Extrusion	Cut lengths of extrudate	Cutting off
Laminating	Cut sheets to size, deflashing edges	Cutting off
Vacuum forming	Polish cut edges, trim parts to size	Cutting off, sanding, filing

With the many different type plastics, there exist a variety of machining characteristics. Like the different metals, nonmetals, aluminums, woods, glasses. etc., different machining characteristics exist. Thermoplastics (TPs) are relatively resilient compared to metals. They require special cutting procedures. Even within the TPs (PE. PVC, PC, etc.) cutting characteristic will change, depending on the fillers and reinforcements used (Chapter 1). Elastic recovery occurs in plastics both during and after machining requiring provisions to be made in the tool geometry for sufficient clearance to allow for it. This is due to the expansion of any compressed material due to elastic recovery which causes increased friction between the recovered cut surface and the cutting surface of the tool. In addition to generating heat, this abrasion affects tool wear. Elastic recovery also explains why, without proper precautions, drilled or tapped-holes in many plastics often are tapered or become smaller than the diameter of the drills that were used to make them (particularly TPs unfilled or not reinforced).

As the heat of conductivity of plastics is very slow. essentially all the cutting heat generated will be absorbed by the cutting tool. The small amount of heat conducted into the plastic cannot be transferred to the core of the shape, so it causes the heat of surface area to increase significantly. If this heat is kept to a minimum no further action is required otherwise heat removed by a coolant is used to ensure a proper cut.

TS plastics machining is slightly different than TPs because there is not any great melting distortion from a fast cutting speed. Higher cutting speeds improve machined finishes. However, the added frictional heat can reduce tool life and the surface of the plastic to be machined can also is distorted in appearance by burning unless precautionary steps are taken, such as spraying a coolant directly on the cutting tool and plastic. Another major difference is the type of chips that are removed by the cutting tool. Almost all of these are in a powder-like form that can be readily removed with the aid of a vacuum hose.

Recognize that all plastics can be properly machined or cut when a few simple rules are observed:

1 use only sharp tools,
2 provide adequate chip clearance,
3 support the work properly, and
4 provide adequate cooling.

Dull tools do not properly cut resulting in a poor surface finish. Because they require greater pressure for cutting, there is unnecessary deflection of the work piece, and excessive frictional heat buildup. Well-sharpened tools scrape properly, leaving a good finish on the work, and remain serviceable for a reasonable length of time.

In many extrusions film and coating operations the slitting and winding must be dealt with as one operation. Figure 18.5 highlights some of the factors that are involved where there is:

1 effect of torque on web tension in center winding,
2 top riding roll riding on gauge band,
3 example of razor blade slitting in air and in grooved roll, and
4 guide to cutting.

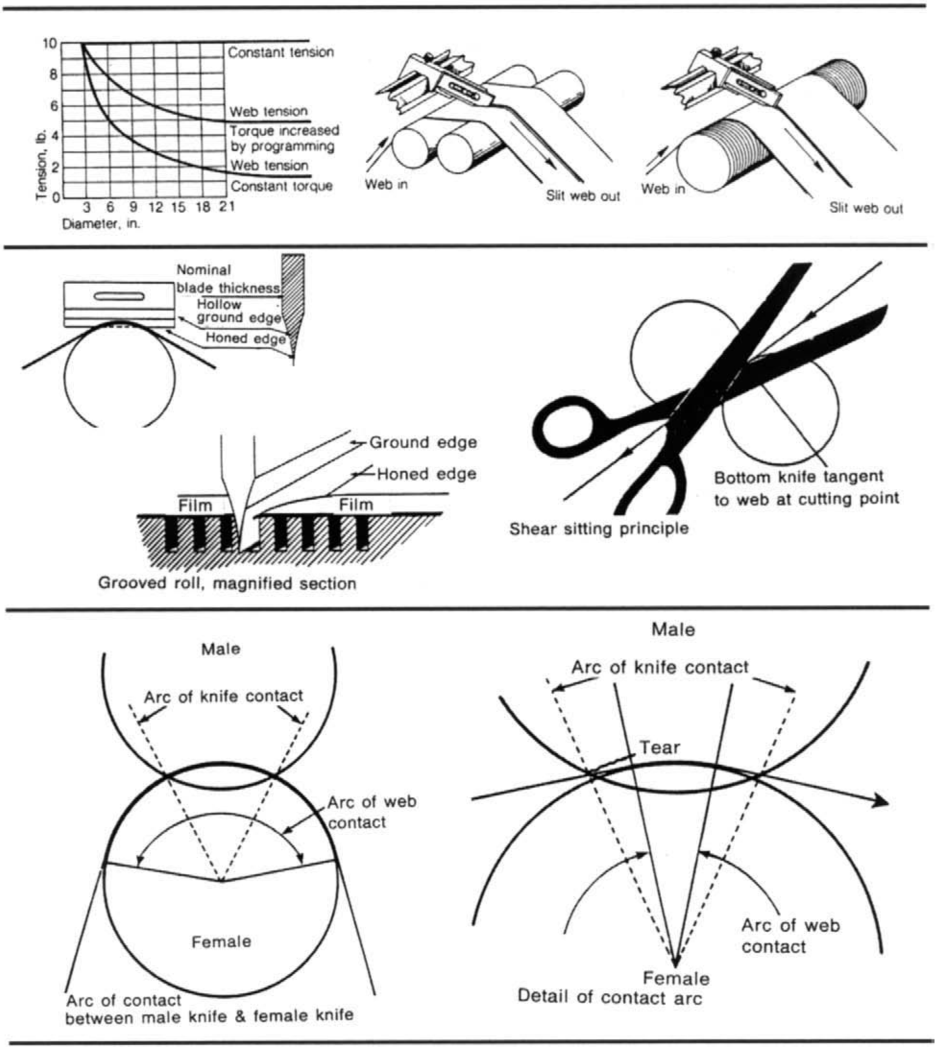
10
8
6
4
2
0
Tension, lb.
3 6 9 12 15 18 21
Diameter, in.
Constant tension
Web tension
Torque increased by programming
Web tension
Constant torque
Web in
Slit web out
Web in
Slit web out
Nominal blade thickness
Hollow ground edge
Honed edge
Ground edge
Honed edge
Film
Film
Grooved roll, magnified section
Shear sitting principle
Bottom knife tangent to web at cutting point
Male
Arc of knife contact
Arc of web contact
Female
Arc of contact between male knife & female knife
Male
Arc of knife contact
Tear
Arc of web contact
Female
Detail of contact arc

Figure 18.5 Guide to slitting extruded film or coating

It is important to prevent the product and cutting tool from heating up to the point where significant softening or melting takes place. There are cutting tools specifically designed to cut plastic that eliminate or reduce the heating problem. Some plastic materials machine much easier and faster than others due to their physical and mechanical properties. Generally, a high melting point, inherent lubricity, and good hardness and rigidity are factors that improve machinability.

Laser cutting is a fast growing process. The laser can act as a materials eliminator. Concentrating its energy on a small spot, it literally vaporizes the material in its path. If the workpiece is held stationary, the laser drills a hole. If the piece is moved, it slits the material. The induced heat is so intense and the action of the laser is so fast that only little heating of the adjacent areas of the piece takes place.

At reduced power output and/or with defocusing of the lens, the laser can be tamed down so that it merely melts material instead of eliminating it, thus offering a scaling process. Using conventional lens systems to focus the beam, holes ranging from about 2 to 50 mils in diameter can be produced. Larger holes can be made by moving the workpiece or the laser tube in a circular fashion so as to slit the piece, much as a band saw would be used to cut a hole.

All these effects are accomplished with no physical contact between the laser and the workpiece. The laser beam has only to focus on the area in which it is to work. Thus laser may easily work areas accessible only with difficulty by conventional tooling and no drill chips are left behind to contaminate or scratch the material. The material removed in laser machining operations frequently is in the form of fine dust that is removed from the area by a suction system.

Other machining methods include high-velocity fluid jet or hydrodynamic machining (HDM) for many plastics. Applications range from slicing 0.75 in. acoustic tile at 250 ft./min. using 45,000 psi to propel the jet at up to Mach 2 speeds, to shaping furniture forms of 0.5 in. laminated paper board. Shoe soles, gypsum board, urethane foam, rubber, and reinforced plastics are cut using the HDM method.

Ultrasonic machining (USM) is also of particular importance when very hard type materials are to be cut. As an assist to drilling, HDM energy can extend the drill life when producing holes in reinforced plastics. If the plastic is conductive, electrical discharge machining (EDM) or electrochemical machining (ECM) may be useful.

New aboard the art of automatic machining is morphing. Morphing involves the transition of one image into another. This morphing approach has been developed by computer-aided design (CAD) software maker Delcam, Birmingham, England. It can reduce hours off lead-time in the modeling or prototype process. Hybrid modeling combines solid modeling and free form surface modeling to facilitate the modeling of complex shapes. It has the ability to change the shape of a product is altered. With the change all surfaces are changed.[368]

When the machining process generates airborne, respirable particles there is cause of safety concern, regardless of the material being machined. OSHA publishes guidelines for the amount of exposure to restorable particles workers should not exceed. The list includes many of the allowing elements such as stainless steel, H13, P20 and other alloying elements (including chromium, vanadium, nickel, copper, molybdenum, and beryllium, (Chapter 17)). To be hazardous, these particles must be smaller than 10 µm, thus are not visible to the naked eye. The large, easily visible particles or chips generated in most machining operations do not represent an inhalation hazard.[166, 167, 168–172, 371]

19 SUMMARY

Overview

As reviewed, millions of different plastic products are produced and used worldwide. Plastics are used in all markets to meet many different requirements. There are endless newly designed products to meet new requirements. Continued research and new technology will extend the future of the plastics industry. Proliferation of new polymers/ plastics manufactured with specific new end use requirements will continue to be developed along with new processing developments.[248, 413–416, 458]

Throughout the 20th century the development of plastics has been extremely spectacular based on its growth rate, but has been even more important in helping people worldwide. The plastic industry is a multibillion dollar business worldwide. Exciting discoveries and inventions have given the field of plastic products vitality. In a society that never stands still, plastics are vital components in its increased mobility.

A continuous flow of new materials, new processing technologies, and product design approaches has led the industry into profitable applications unknown or not possible before. What is ahead will be even more spectacular based on the continuous new development programs in materials, processes, and design approaches that are always on the horizon to meet the continuing new worldwide industry product challenges.[22, 54, 63-66, 100, 136, 398-401, 406–412, 417–420, 424, 451, 460, 461]

Research and development

The extent to which plastics are used in any industry in the future will depend in part upon the continued total research and development

(R&D) activity carried on by materials producers, equipment suppliers,[476] processors, fabricators, and users in their desire to broaden the scope of plastics applications. The bulk of such research expenditure is done by the materials producers themselves followed by equipment suppliers, and the rest by the user industries who do more than the processors and fabricators whose share is small.

As an example of special interest has been the discovery and applications of stereospecific polymerization. This process uses special catalysts to yield materials in which the molecules have predetermined structures. The configuration of polymer molecules and the manner in which they form crystals comes under the heading of morphology (Chapter 1). Some plastic materials have crystalline internal structures just as the metals do and undergo some similar reactions during processing. These advances in scientific knowledge result in their use for the improvement of present polymers, followed by the design of new polymers and copolymers to obtain specific end use products. For example, polymer chemists believe that cross linkages occur preferentially at the surfaces of the crystals. These studies and the mechanism by which the crystals are held together and relocated during processing when the shape of the material is changed ultimately results in improved understanding of the physical properties of polymers and the methods by which they may be formed and fabricated.

Theoretical vs. Actual Value

Through the laws of physics, chemistry, and mechanics, in 1944 theoretical data was determined for different materials.[402] These are compared to the present actual values in Table 19.1. With steel, aluminum, and glass the theoretical and actual experimental values are practically the same, whereas for polyethylene, polypropylene, nylon, and other plastics they are far apart, and have the important potential of reaching values that are far superior to the present values.

When polyethylene was first produced in the early 1940s, physicists in England, USA, and Germany predicted a tremendous potential for it. At that time the properties of PEs were much lower than those presently available. Out of that original general-purpose PE, have been developed specific PEs such as LDPE, HDPE, UHMWPE, and so on (Chapter 2).

Smarter Plastic

Another example of many developments is the new plastics being created by chemical engineering researchers at Rensselaer Polytechnic Institute, Troy, NY. The target is to improve medical care and other

Table 19.1 Comparison of theoretically possible and actual experimental values for properties of various materials

	Modulus of Elasticity			Tensile Strength		
		Experimental			Experimental	
Type of Material	Theoretical, N/mm² (kpsi)	Fiber, N/mm² (kpsi)	Normal Polymer, N/mm² (kpsi)	Theoretical, N/mm² (kpsi)	Fiber, N/mm² (kpsi)	Normal Polymer, N/mm² (kpsi)
Polyethylene	300,0000	100,000	1,000	27,000	1,500	30
		(33%)	(0.33%)		(5.5%)	(0.1%)
	(43,500)	(14,500)	(145)	(3,900)	(218)	(4.4)
Polypropylene	50,000	20,000	1,600	16,000	1,300	38
		(40%)	(3.2%)		(8.1%)	(0.24%)
	(7,250)	(2,900)	(232)	(2,300)	(189)	(5.5)
Polyamide 66	160,000	5,000	2,000	27,000	1,700	50
		(3%)	(1.3%)		(6.3%)	(0.18%)
	(23,200)	(725)	(290)	(3,900)	(246)	(7.2)
Glass	80,000	80,000	70,000	11,000	4,000	55
		(100%)	(87.5%)		(36%)	(0.5%)
	(11,600)	(11,600)	(10,100)	(1,600)	(580)	(8.0)
Steel	210,000	210,000	210,000	21,000	4,000	1,400
		(100%)	(100%)		(19%)	(6.67%)
	(30,400)	(30,400)	(30,400)	(3,050)	(580)	(203)
Aluminum	76,000	76,000	76,000	7,600	800	600
		(100%)	(100%)		(10.5%)	(7.89%)
	(11,000)	(11,000)	(11,000)	(1,100)	(116)	(87)

[a] For the experimental values the percentage of the theoretically calculated values is given in parenthesis

applications by producing smarter plastics. Their approach is to embed the plastic with enzymes, Protein-enhanced plastics might some day be able to act as ultra-hygienic surfaces or sensors to detect the presence of various chemicals. Proteins require water to function, however non-watery environments do not provide the driving force necessary to keep proteins in their normally intricately folded state. Unfolded the molecules cease to function. Molecular dynamics simulations are prepared to create computer model of the proteins and study the molecules in watery and non-watery environments such as organic solvents. The challenge is to find ways to manipulate the enzyme to function optimally in those environments. Use of the plastic could provide unique benefits such as extending the life of implants or other in vivo materials, reducing the risks of infection or rejection, and so on.[463]

Equipment development

One of many examples of a future process development has been introduced. It will use laser and microwave plasticators, fiber-optics monitoring, quiet electromagnetic drives, voice-activated controls, permit quick plastic changes without purging, eliminate hoppers by storing plastics in modular tanks on the machine's bed and feeding by vacuum pumps behind the plasticators, and more innovations. Features to be gained include more energy savings, increase process efficiencies, and simplify controls so that the IMMs will be easier to operate, and improve and provide repeatability of melts. This program called Mother Project was started in 1999 and targeted to be completed by 2017. Studies are being conducted by MIR, S.p.A, Italy in cooperation with the University of Turin's Plasturgy Dept.; USA agent MIR USA, Leominster, MA.

Product development

Only a few recent product developments will be reviewed. There are many more which have all kinds of significant aid and importance to people worldwide.

Composite Commercial Airplane

With the performance to weight advantages of carbon fiber the 200 to 250 passenger Boeing 7E7 high speed jet (mach 0.85) light weight commercial airplane will have the majority of its primary structure (wings, fuselage, etc.) made of carbon reinforced composites. It will use 15 to 20% less fuel when compared to other wide-body airplanes. Production will begin in **2005**. First flight is expected in **2007** with certification, delivery, and entry into service **2008**.[465]

Bonding Plastic

The University of Massachusetts Lowell received patents pertaining to a method of bonding plastic components developed by Avaya, Inc., a Basking Ridge, NJ based provider of corporate net-working solutions and services. Reportedly valued at about $23 million, the patented technology was developed in the early 1990s for the high-speed bonding of thermoplastic parts, and has been used to assemble millions of telephones, etc. The University licenses the technology to others for use in a wide range of commercial applications. UMass-Lowell will also commit resources to further develop the technology and incorporate it into the school's curriculum.

Self-Healing RP

The University of Illinois developed a technology for repairing hairline cracks in RPs by embedding microcapsules containing monomers corresponding to the plastic matrix.[403, 404]

Airbus Super-Jumbo RP Wing Parts

GKN Aerospace Services/Cowes, UK is fabricating wing trailing edge panels for the new (present count) 350-seat A380 Airbus. It will be made from glass and carbon fiber RP using GKN's resin fusion process.[47]

World's Largest Wind Blade

German wind turbine company REpower Systems AG has joined forces with Denmark's LM Glasfiber to develop an RP blade for REpower's SM turbine, a 5 MW machine with a rotor diameter of over 125 m. It will be the largest blade in the world in serial production. The prototype should be completed by the end of 2003. From 1978 to 2001 LM fabricated over 60,000 RP blades of smaller sizes for wind farms.[48, 49]

Bridge Infrastructure and RP

Use of RPs to support deteriorating bridges has been on going and expected to significantly expand. The Road Information Program (TRIP), non-profit transportation research group in Washington, DC reported that 1 in 4 of USA's major heavily traveled bridges is deficient and in need of repair or replacement. Due to significant deterioration 14% are structural deficient.[405]

Design demand

It can be said that the challenge of design is to make existing products obsolete or at least offer significant improvements. Despite this level of activity there are always new fields of industry to explore.[482] Plastics meet this challenge and will continue to change the shape of business rapidly. Today's plastics tend to do more and basically overall cost less, which is why in many cases they came into use in the first place. Tomorrow's requirements will be still more demanding, but with sound design, plastics will satisfy those demands, resulting not only in new processes and materials but in improvements in existing processing and materials.

Plastics in the forefront

In the future plastics will continue to contribute significantly worldwide towards a sustainable economy. They will continue to provide a vital role in people's daily lives. As the world's population increases, plastics, as usual, will meet new developing challenges by providing solutions without compromising the needs of future generations. With all this action, global consumption of plastics, with its continuing new developments in plastic materials and processing, will continue to rise. Accompanying this action will be the continued advancement of technology in the "art" of producing plastic products.

Plastics is one of the most important business sectors providing significant contributions to the economy and standard of living across all sectors worldwide. Based on the continuing trend where USA manufacturing leaves USA the help Save American Manufacturing (SAM) organization was formed in early 2003. It is taking positive action in this dilemma by educating politicians throughout USA and particularly Washington, DC.[478–480]

Summarization can be made as to what has been occurring in the World of Plastic. It can be said that no other materials have had such a lasting impact on virtually all spheres of life. What is more interesting and important with plastics is the endless new development in all facets going from plastic materials to equipment to products to markets. They have successfully conquered broad sections of virtually all spheres of life demonstrating dynamic development from their infancy to futuristic, highly specialized, high-tech applications. No industry is more future oriented than the plastic industry, with continual growth materialwise, processwise, and productwise.[53, 65, 475]

REFERENCES

1 Rosato, D. V., Plastics Mechanical Engineering Design Handbook, Elsevier, 2003.

2 Rosato, D. V., Designing with Plastics, Kluwer, 2001.

3 Rosato, D. V., Injection Molding Handbook, 3rd Ed., Kluwer, 2000.

4 Rosato, D. V., Designing with Reinforced Composites, Hanser, 1997.

5 Rosato, D. V., 'Materials Selection & Reinforced Plastics-Thermosets' in Concise Encyclopedia of Polymer Science and Engineering, J. I. Kroschwitz (ed.), Wiley, 1990.

6 Rosato, D. V., Materials Selection Chapter in Encyclopedia of Polymer Science and Engr., Mark-Bikales-Overberger-Menges (eds.): Vol. 9, pp. 337–379, Wiley, 1987.

7 Caraballo, W., Flexibility and Customization Expand Packaging Options (Thermoform-Fill-Seal), MD&DI, Jan. 2002.

8 Colors are Brewing for PET Beer Bottles, PE, Feb. 2002.

9 High Hopes for Beer Bottles Enliven Packaging Conferences, PT, Jan. 2000.

10 Keeping Up with Materials, PT, Jan. 2002.

11 King, R. D., et al., Future belongs to Biopolymers, MP, Jan. 2000.

12 Lauzon, M., Wood-fiber Uses Moving Beyond Decking, PN, Jun. 10, 2002.

13 Ogando, J., Plastics Will Survive High-Volt Jolt, DN, Oct. 1, 2001.

14 Sherman, L. M., The New Polypropylenes, PT, May 2002.

15 Sterbenz, c. e., One Word: Plastics, The Providence, Jul. 2, 2000.

16 Sterbenz, c. e., One Word: Plastics, The Providence, Jul. 2, 2000.

17 Thermoplastics in Major Markets, PE, May 2000.

18 Composite Material Throws Competition a curved Ball, Horizon, BP Publ., Aug. 2002.

19 Schut, J. H., Foamed Films Find New Niches, PT, Feb. 2002.

20 Toensmeier, P. A., Blown Film Equipment and Resin Upgrades, MP, Aug. 2002.

21 Kutz, M., Handbook of Materials Selection, Wiley, 2002.

22 Blanco, A., Biodegradable-Just Add Water, PE, Oct. 2002.

23 Johnson, B. P., The Use of a Design of Experiments (DOE) to Optimize Processing Conditions of an Injection Molded Gear, SPE ANTEC, 2002.

24 Johnson, J., Streamlining Polymer Selection for E/E Applications, PE, Jan. 2002.

25 Moore, S., Innovative Reactive Extrusion Technologies bring Added Value to Recycled Plastics, MP, Jan. 2000.

26 Price, P., Nanotechnology: The Next Big Thing is Really Small, Horizon, BP Publication, Apr. 2002.

27 Stewart, R., Higher-Output Extruders, Precision Controls Aim to Boost Productivity and Profitability, Plastics Engineering, Aug. 2003.

28 Thermoformed (Coextruded Plug-Assisted Twin-Sheet) Fuel Tanks Show Promise, MP, Apr. 2000.

29 Two New Ideas for Injection Molding Unveiled at ANTEC Meeting, PT, Aug. 2002.

30 DeFosse, M., Material and Process Developments (Pultrusions) Promise New Applications, MP, Jun. 2002.

31 Shortt, M., Cryogenic Processing an Exciting Frontier for Manufacturers, Job Shop Technology, Feb. 2002.

32 Vaughan, R., Designing the Moldmaking Industry's Future, MoldMaking Tech., Sep. 2002.

33 Rauwendaal, C., Polymer Extrusion, 4th Edition, Hanser, 2001.

34 Stretch Blow Molding Produces PET Cups, PN, Sep. 2, 2002.

35 Facts & Figures of the U.S. Plastics Industry, Annual updates.

36 Leventon, W., Medical Tubing Offers More (and Less) to Device Makers, MD&DI, Jan. 2002.

37 Marsh, G., Flying High with the Self-Build Movement, RP, Jan. 2002.

38 Neilley, R., The Art of Fine-Tuning a Micro-Molding Business, Europe, Jan. 2002.

39 Plastics Applications, PE, Apr. 2002.

40 Renstrom, R., Sliding Zippers Find Favor Among Packagers, PN, Mar. 18, 2002.

41 Salerni, C. M., Selecting Engineering Adhesives for Medical Device Assembly, MD&DI, Jun. 2000.

42 Toothpaste in Tubes 100 Years and Still Going, Tube Council Of North America, Tube Topics, Vol. 26, No. 3, 1992.

43 MACT: A More Restrictive World for Boatbuilders: RP, Jan. 2002.

44 Johnson, J., Streamlining Polymer Selection for E/E Applications, PE, Jan. 2002.

45 Dowhower, K., et al., Seals Upgrade Connectors, DN, Dec. 17, 2001.

46 Kirkland, C., Metrics for High-Volume, Accurate Micromolding, IMM Focus, Jul. 2002.

47 GKN Aerospace to Build A380 Wing Parts, RP, Sep. 2002.

48 World's Biggest Blade, RP, Sep. 2002.

49 Wind Energy Supplement, RP, May 2003.

50 Extruded RR Ties Take a Cool Bath, PT, Oct. 2002.

51 Franz, A. et al., Introducing New Injection Molding Technologies into Small and Medium Sized Enterprises, SPE IMD Newsletter, Issue 57, Summer 2001.

52 More Packaging Gains, World Plastics Technology, 2002.

53 Toensmeier, P. A., CDs have made Sweet Music with Plastics for 20 Years, MP, Sep. 2002.

54 Composite Organic Materials Could Yield Stronger Artificial Muscles, MD&DI, Nov. 2002.

55 Packaging and Automotive Top the News, PT, Jan. 2002.

56 Auto Manifold, Reinforced Plastics, June 2001.

57 Mapleston, P., Plastics are Primed for Big Push in Auto Exteriors, MP, Jul. 2002.

58 Miel, R., Plastics Use May Rise if Auto Voltage Changes, PN, Jun. 10, 2002.

59 PP is on the Fast Track in Automotive, Mastio & Co., PT, Jan. 2002.

60 These Fuel Tanks Flex, DN, Mar. 26, 2002.

61 Toyota will Use SMC Boxes for Truck Beds, MP\, Aug., 2002.

62 Leaversuch, R., Thermoforming Shines in Exterior Vehicle Panels, PT, Nov. 2002.

63 Shortt, M., Time-Saving Innovations are Key to New Product Development, Job Shop Tech., Aug. 2002.

64 Wolfe, The Future is Now-Innovate, DN, Aug. 20, 2001.

65 Technology Drives Growth, World Plastics Technology, 2002.

66 Cost, Performance Help PVC Stave off TPO in Auto Interiors, MP, Dec. 2002.

67 Jaguar Adopts Long Fiber Technology, RP, May 2003.

68 Crosslinked PE to Expand in Heating, Plumbing Pipe, MP, JaN. 2003.

69 DeRosa, A., PEX Pipe Makers Tout Improved Products, PN, Feb. 24, 2003.

70 Scaeberle, M., et al., Raman Chemical Imaging : Noninvasive Visualization of Polymer Blend Architecture, Analytical Chemistry, 67, pp. 4316–21, 1995.

71 Catalyst Lets Sumitomo Double LCP Capacity, MP, Jan. 2003.

72 Deanin, R. D., University of Massachusetts-Lowell correspondence, 2000.

73 Sherman, L. M., Metallocene VLDPE is a Tough New Contender for Flexible Packaging, PT, Jan. 2002.

74 Wigotsky,V., Compounding, PE, Jan. 2002.

75 North American Plastics Recyclers and Brokers 2002 Survey, PN, May 20 & 26, 2002.

76 Recycling at K 2001, PT, Feb. 2002.

77 Schut, J. H., Big German Plant May Relieve U.S. Bottleneck in Recycling Carpet nylon, PT, May 2002.

78 Schut, J. H., Entrepreneur Puts Mixed Polymer Recycling On Track to Success, PT, May 2003

79 Esposito, F., Resin Makers to Announce New Products, PN, May 2003.

80 Plastic Fuel Tank Meets PZEV Regulation (vehicle emission rate), PE, May 2003.

81 Engineering Materials Handbook, Vol. 2: Engineering Plastics, ASM International, 1988.

82 High Temperature Polyolefin Fibers and Yarns, PE, May 2003.

83 Colvin R., Heavy-Duty, Self-Sealing Bag Challenges Paper Sacks, MP, Mar. 2003.

84 TPVs Can Withstand Higher Temperatures, PN, Apr. 28, 2003.

85 Get a Grip (Santoprene), PE, Feb. 2003/

86 TPVs Do Windows (and Doors), PE, Feb. 2003.

87 TPEs Goes Where Others Cannut, PE, Dec. 2002.

88 Automotive, Soft-Touch Markets Promise Strong Year (TPEs), MP, Feb. 2003.

89 Non-Blooming, Non-Fogging UV Stabilizer for TPOs, PT, May 2003.

90 Toensmeier, P. A., Stretch Film Provides Shrink film Performance, MP, Mar.2003.

91 Thedinger, B., Trash Bags & Liners Grow at Rate of GDP, PT, Mar. 2003.

92 ExxonMobil Adds mLLDPE with Higher Densities, PT, Feb. 2003.

93 Dow Discovers New Class of Post-Metallocene' Polyolefin Catalyst, PT, May 2003.

94 Materials Data, PE, Apr. 2002.

95 Combining Metallocene Technology with Gas Phase EPDM, PE, Feb. 2003.

96 Heller, M. A., Guide to Medical Device Regulation, Thompson Publ. Group, Inc., 2003.

97 BOPP Film Demand in North America, PN, May 5, 2003.

98 Defosse, M., Public's Education is Key to Vinyl's Acceptance, MP, Jun. 2002.

99 Environmental Briefs, The Vinyl Institute, May 2000.

100 Toensmeier, P. A., Vinyl Forum has Value for the Public, MP, Dec. 2002.

101 Toloken, S., PVC Blend Improves Blood-Clotting Options, PN, Mar. 3, 2003.

102 Gaukroger, T., Adding Process Flexibility to Rigid PVC, PE Europe, May 2003.

103 Annual Vinyl Window Market Growth, PN, Feb. 3, 2003.

104 Annual Vinyl Siding Market Growth, PN, Apr. 28, 2003.

105 DeFosse, M., Mature Industry Still Has Room for Growth (PVC), MP, Feb. 2003.

106 There's lots New in Acetal, PT, May 2003.

107 Rosenzweig, M., Tough Auto Requirements Drive Fluoroelastomers Growth, MP Jan. 2003.

108 Auto Industry Drives European Fluoropolymers, PE Europe, May 2003.

109 Fluoropolymer is a Better Barrier for Fuel Hoses, PT, Mar 2003.

110 Modified PTFE Improves Properties and Processing, PT, May 2003.

111 Right Inside the GearBox: Polyamide 6.6 Stands the Heat in BMW 7 Series, Polymotive, Feb. 2, 2003.

112 PBT Designed for Use with Water-Assist Molding, PM&A, May 2003.

113 Dow Unit to Market Cyclics PBT Materials, PN, Apr. 28, 2003.

114 Structural Products has 8 New Offerings (GE/PC), PN, May 12, 2003.

115 Renstrom, R., Downloading to Hard Drives could Shrink Market for (PC) Discs, PN, Mar. 10, 2003.

116 Taking the Heat (polyester transparent, thermoformable sheet), PE Europe, May 2003.

117 PEEK Preview, PE Europe, May 2003.

118 PET Boost for Bottled Beer, PE Europe, May 2003.

119 Shrink-Sleeve Polymer (for PET bottles), PE, May 2003.

120 Wide Mouth PET Bottles Get OTE Closures (outside tamper evident), PT, May 2003.

121 Polysulfone on a Power Trip, PE, Jan. 2003.

122 Klempner, D., et al.,. Advances in Urethane Science and Technology, Rapra Technology Ltd., 2002.

123 Cutting Down on Freeze-Ups (TPUs), PE, Feb. 2003.

124 TPUs Get a Grip On Overmolding, PT, May 2003.

125 Wheelchair Cushions Rest on TPU Attributes, PE, May 2003.

126 Knights, M., LSR (Liquid Silicone Rubber) Finds an Old Trick can Overcome New Challenges, PT, Feb. 2003.

127 North American Recycling Market, PN, May 26, 2003.

128 Shut, J. H., Recycling Conference Shows Off New Ways to Enhance Recycled Plastics, PT, May 2003.

129 Toloken, S., Chicago Getting All-Bottles Recycling Site, PN, Jun. 2, 2003.

130 Sefosse, M., Wood Composites are Expanding Among Sectors (with recycled plastics), MP, Jan. 2003.

131 Railway Ties Gain Ground, MP, Feb. 2003.

132 New Materials and Processing – Design Success, Design News, Apr. 23, 2000.

133 Markets May Warm Up to Thermochromic Effects, MP, Mar. 2003.

134 Mapleston, P., End-Users Fire Up Demand for High Heat Thermoplastics, MP, Jun. 2002.

135 Naitove, M., Editorial, PT, Jan. 2003.

136 Market Data Book, PN, Dec. 30, 2003.

137 SPI Issues Third-Quarter Equipment Sales Statistics, PE, Jan. 2003.

138 Capacity Utilization for Plastic Product Manufacturing, PN, Feb.17, 2003.

139 Japan's Exports and Imports of Plastics/Rubber Processing Equipment, PN, Feb. 24, 2003.

140 Firenze, A. R., The Plastics Industry, Adaptive Instruments Corp., Hudson, MA 01749, 2000.

141 Rosato, D. V., The Impact of New Machinery in '76, SPI New England Fall Conference, Portsmouth, NH, Oct. 5–7, 1966.

142 Mapleston, P., Specialized Techniques, MP, Jun.2002.

143 Rosato, D. V., Extruding Plastics: Practical Processing Handbook, Kluwer, 1998.

144 Colby, P. N., Plasticating Components Technology: Screw & Barrel Technology, Spirex Bulletin, Spirex Corp., 2000.

145 Bernhardt, A., et al., Rationalization of Molding Machine Intelligent Setting & Control, SPE-IMD Newsletter, No. 54, Summer 2000.

146 Finan, J. M., Thermally Conductive Thermoplastics, PE, May 2000.

147 Coleman, B. D., Thermodynamics of Materials with Memory Treatise, Arch. Rat. Mech. Anal., 1964.

148 Moore, S., Preventive Purging has Practical Benefits, MP, Sep. 2002.

149 Van Haste, F., Chemical Purging: When and How to Do It Right, PT, Feb. 2003.

150 Leventon, W., Part Making on a Very Small Scale: Micromolding for Medical Devices, MD&DI, May 2002.

151 Harris, H. E., Controls and Instrumentation, MP Encyclopedia, 1986–1987.

152 Sheble, N., Temperature Measurement a Matter of Electronics, ISA Sensor Technology, Jan. 2002.

153 PID Controller Saves Space, Yet Maintains High Performance, Plastics Auxiliaries & Machinery, Jan/Feb. 2002.

154 Fierens, B., et al., ISO/QS Process Certification: Measuring the Proper variables, SPE ANTEC, 1999.

155 Temperature Settings, IM, Feb. 2002.

156 Wiczer, J., New Efforts to Streamline Smart Sensor Standards, ECN, ep. 2003.

157 Rucinski, P., Manufacturing Solutions for the Automation, Control, and Monitoring of the Injection Molding Process, SPE IMD Newsletter, Issue 59, Spring 2002.

158 Moldflow Corp., 91 Hartwell Ave., Lexington, MA 02421, tel. 781-674-0085, Fax +1-781-674-0267, http://www.moldflow.com, http://www.cmold.com.

159 DCS, PLC, and PC Technologies Converge in New Breed of Hybrid Controllers, InTech, Jan. 2003.

160 Brazier, G., Safe Wireless Sensing, InTech, May 2003.

161 Extrusion monitoring Goes Wireless, PT, May 2003.

162 Herb, S., Weapon for Mass Production; Distributed Microprocessing Without the Traditional Complexity, Cost, and limits, InTech, Aug. 2003.

163 Rauwendaal, C., Look Out for Metal-to-Metal Wear, PT, May 2003.

164 Rosato, D. V., Blow Molding Handbook, 2ed Edition, Hanser, 2003.

165 Jovalusky, J., Integrating Circuit-Protection Functions Reduces Power Source Costs, ECN, Jun. 2003.

166 Watkins, F., et al., Control Technologies for Safety and Productivity, InTech ISA, Feb. 2002.

167 Colvin, R., Automated Roll Handling Boosts Cast Film Operations; Cost Plays a Secondary Role to Improved Productivity, Quality, and Safety, MP Nov. 2000.

168 Rosato, D. V., Nick's Notes: Safety Issue, Molding Views, Injection Molding Division Newsletter of SPE, No. 60, May 2002.

169 Pockham, G., Safety Sign Formats, Compliance Engineering, May/June 2002.

170 The Importance of Safety Agency Listing, Compliance Engineering, May/June 2002.

171 Rosato, D. V., What Molders Must Do about ANSI Safety Specifications, PW, Apr. 1978.

172 Rosato, D. V., Plastics Industry Safety Handbook, Cahners, 1973.

173 Rosato, D. V., Injection Molding Chapter: R. F. Jones book Guide to Short Fiber RP, Hanser, 1998.

174 Rosato, D. V., Injection Molding Higher Performance Reinforced Plastic Composites, J. of Vinyl & Additive Technology, Sep. 1996.

175 Bozzelli, J. W., Going from Hydraulic to Electric: Processor's Perspective, IMM, 2002 Annual.

176 Snyder, M. R., Milacron Launches Internet-Based Link for Injection Molding Machine Diagnostics, MP, Jul. 2000.

177 Robot 2004 Worldwide Directory, Robotics World/Motion Control, July/Aug. 2003.

178 Shad Foresees Consolidations Continuing, PN, May 5, 2003.

179 Electric Machines and New Processes Catch Fire, PT, Jan. 2003.

180 Schut, J. H., Interchangeable Dam Adds Versatility to Screw, PT, Jan. 2003.

181 SPC System Meets Custom Applications, IM, Jul. 2002.

182 Larsen, A. N., et al., Is the Shear Heating Phenomenon Truly Responsible for Viscosity Reduction in Thermoplastic Injection Molding? SPE ANTEC, 1998.

183 Dealy, B., Size Does Matter for Injection Units, MP, Jul. 2002.

184 Mapleston, P., Cavity Pressure Control System, MP, Jun. 2002.

185 Demirci, H. H., Process Window Identification for a very Tight-Tolerance Injection Molded Part with Multiple Performance Criteria, SPE ANTEC, 2001.

186 Schott, N., et al., Optimization in Process Control for uniform Quality of the Optical Components, SPE ANTEC, 2001.

187 Coxe, M., et al., The Establishment of a Processing Window for Thin-Wall Injection Molding of Syndiotactic Polystyrene, SPE ANTEC, 2000.

188 Knights, M., Gas Assist Works for Thermosets and Smaller Parts, Too, PT, May 2003.

189 Juntgen, T., et al., The Water Injection Molding Technique (WIT) as an Attractive Alternative and Supplement to Gas-Assisted Injection Molding (GAIM), SPE ANTEC, 2002.

190 Water Injection Technology Used in Injection Molding, Polymotive, Feb. 2003.

191 Hollow to the Core, PE Europe, May 2003.

192 Juntgen, T., et al., The Water-Injection Technique (WIT) as an Attractive Alternative and Supplement to Gas-Assisted Injection Molding (CAIM), SPE-IMD Molding News, No. 61, Winter 2003.

193 Tustison, L., Overmolding Overview, IM, Jul. 2002.

194 Cha, S., etal., 3–D Simulation of Thin-Wall Injection molded Parts by CAE, SPE IMD News, May 2002.

195 Extrusion List: Buyers' Guide, SPE, Aug. 2003.

196 White, J., et al., Screw Extrusion, Hanser, 2003.

197 Moore, S., Reactive Extrusion Aids Bottle-to-Bottle Recycling, MP, Mar. 2003.

198 Schut, J. H., Torque and Speed: How Much is Enough? PT, Sep. 2002.

199 Toensmeier, P. A., Package Design Advances Enhance Brand Awareness, MP, Feb. 2003.

200 Waller, P., Melt Fracture or Interfacial Instability? Different Ills Needs Different Cures, PT, Mar. 2003.

201 Gillard, L., Custom Cable Embraces a World of Conductors, ECN, June 2003.

202 First Nylon/Acrylate TPVs are Now Commercial, PT, May 2003.

203 Castillo, R., Coextrusion Die Design Doubles Number of Layers for Packaging Films and Blow Molding Parisons, SPE ANTEC, 2001.

204 Thielen, M., Blow Molding, Sequential Coextrusion: Advanced Technology Opens Door into a New World of Tailored Parts, Modem Plastics Encyclopaedia, 1999.

205 Schut, J. H., Stretching Film's Limit (5–to-7–to-9), PT, Feb. 2003.

206 Coextruding Multilayer Blown Film, Dow Chemical Co., 1970s.

207 Toensmeier, P. A., Flex Tech Stakes Its Future on success of Coex MDO, MP, Feb. 2003.

208 Emboss Film Without Heat, PT, Feb. 2003.

209 Changing Market in Compounding Machinery, PE Europe, May 2003.

210 Schut, J, H., Long-Fiber Thermoplastics Extend their reach, PT, Apr. 2003.

211 Rosato, D. V., Concise Encyclopedia of Plastics, Kluwer, 2000.

212 Rosato, D. V., Current and Future Trends in the Use of Plastics for Blow Molding, SME, 1990.

213 Defosse, M., Large Blow Molded Containers Take Off, MP, Apr. 2000.

214 Blow Molding Higher Output Vies with Flexibility, PT, May 2003.

215 Thedinger, B., Blow Molded Drums, IBCs, and THPs Stuck in Low Gear, PT, Jan. 2003.

216 O-I Launches See-Through PET Beverage Can, PT, Jan. 2003.

217 European Union Gives Tetra Laval the Green Light to Acquire Sidel, MP, Feb. 2003.

218 Pryweller, J., Blow Molders Showcase Stock, PN, May 5, 2003.

219 Plastics Pipe Institute, 100–Year Design Life Cited for Corrugated HDPE Pipe, PT, June 2003.

220 Leaversuch, R., Blow Molding Equipment, PT, June 2003.

221 Keener, C. et al., Optimizing Extrusion Blow Molding for Multilayer Container Production, Graham Machinery Group, York, PA, Aug. 15, 2001.

222 Leaversuch, R., All-Electric & Stretch Blow Get Top Billing, PT, Jan. 2002.

223 Leaversuch, R., Super-Clear PP Barrier Bottles are Now (Injection) Blow Molded, PT, Feb. 2003.

224 Naitove, M. H., Injection Blow Molding COC (cyclic olefin copolymer) Arrives: Here's How to Do It, PT, Mar. 2003.

225 Defoose, M., Soft-Drink Giants Stae Interest in Multilayer Packaging Alternatives, MP, Feb. 2003.

226 Toensmeier, P. A., Kortec Readies 144 Cavity Coex PET Preform Mold, MP, June 2003.

227 Moore, S., Two-Stage Stretch (Injection) Blow Process Claims Benefits for Drink Cups, MP, Jan. 2003.

228 Lee, N. C., Control Flash in Extrusion Blow Molding, PT, Sep. 2002.

229 Freeman, R., Pressure Forming with Style, SPE Thermoforming Quarterly, Spring 1999.

230 Throne, J. L., Technology of Thermoforming, Hanser, 1996.

231 Defoose, M., Fuel Tank Makers Appear to Ease Off Thermoforming, MP, Sep. 2002.

232 McConnell, W. K., Ten Fundamentals of Thermoforming, SPE, 2002.

233 Gerber Products Invests in Plastic (Thermoformed Baby) Jars, PN, May 26, 2003.

234 North American Thermoformers (Packaging & Industrial End Markets), PN, Feb. 10, 2003.

235 When Far East Meets South/Thermoformers Used by Chinese Appliance Maker, PN, June 2, 2003.

236 Thermoforming Buyers' Guide, PE, Feb. 2003.

237 Top Ten North American Thermoformers, PN, Feb. 10, 2003.

238 Toensmeier, P. A., Automotive is Fertile Ground for Growth, MP, Nov. 2002.

239 Thermoforming Nylon, PE, May 2003.

240 All PP Composites Could Challenge GMT (Glass-Mat-Thermoplastic) in Markets, MP, June 2003.

241 PLA (polyactic acid) Makes U.S. Debut in Thermoforming (Food) Packaging, PT, May 2003.

242 Meinzinger, D., Thermal Expansion of Plastics, SPE Thermoforming Div. Newsletter, Vol. 20, No.1, 2001.

243 Hard Fact: Packaging (Blister) Can Save Kid's Lives, PN, Feb. 24, 2003.

244 Form/Fill/Seal Machine Targets Bottle Blow Molding, MP, June 2003.

245 Melt=Phase Billet Rorming Adds New Option for Containers, PT, Jan. 2003.

246 Murray, C. J., Foam Exhibits Negative Poisson's Ratio, DN, Dec. 1989.

247 Microcellular Foam Technology, IMM, Dec. 2001.

248 Osswald, T. A. & G. Menges, Material Science of Polymers for Engineers, 2nd Edition, Hanser, 2003.

249 Meeting the dead Line: Urethane Foams Move from HCFCs to 'Cleaner' Blowing Agents, PT, Jan. 2003.

250 Hoechtlen, A. and Droste, W., (to I.G. Farbenindustrie A.G.) DRP 913, 474, Apr. 20, 1941 (Japanese Patent Publication No. Sho-31–7541).

251 Flame Retardant Agrees with Montreal Protocol, PE, Jan. 2003.

252 Sherman, L. M., Polyurethane: Get Ready for HCFC Phase-Out, PT, Dec. 2001.

253 Sentinel Products Introduces Expanded PP Sheet, PN, June 2, 2003.

254 Foam Polystyrene with Nanoclay and CO_2, PT, May 2003.

255 PUR Flushing Solvents Leave Less Residue, PT, May 2003.

256 Recycling PUR Foam is Gleaned from Mattresses, MP, Feb. 2003.

257 Trexel Licenses Users of Demag Ergocell System, PT, Dec. 2001.

258 Elden, R. A., et al., Calendering of Plastics, London Iliffee Books, 1971.

259 Compunding and Mixing, PT, June 2003.

260 Haberstroh, E., et al., In-Mold Film Method Targets PUR Exteriors (Autos), MP, Sep. 2002.

261 Automotive Paint-Finding the Right Formula, Polymotive, Feb. 2003.

262 Polymer Glass Coating Creates Germ-Free Surfaces, MD&DI, Jan. 2002.

263 Snyder, C. D., Materials for Reaction Injection Molding Processing, Composite Fabrication Assoc., Oct. 3–6, 2001.

264 Palmosina, M. F., Gating for the Reaction Injection Molding Process, Bayer Corp., Pittsburgh, PA, 2002.

265 Rosato, D. V., Plastics Processing Data Handbook, Kluwer, 2nd Ed., Kluwer, 1997.

266 Integral Skin Foam Protects Fancy Tires, PT, Sep. 2002.

267 Poly-DCPD RIM Shifts into High Gear, PT, Sep. 2002.

268 Frederick, C. D., et al., Rotational Molding, Plastics Solutions International 2000.

269 Rotational Molding Transforms Movie Characters into Merchandise, Job Shop Tech., Aug. 2002.

270 Rotational Molders-Listing, Ranking, and Survey, PN, Aug.11, 2003.

271 Bregar, B., Research Shows Promise for Rotomolded PP, PN, Aug. 5, 2002.

272 Rotomolders get New Alternatives to XLPE, PT, Sep. 2002.

273 Chroma Corp., McHenry, IL, Attention Rotomolders: Clean Air Mixers Faster, PT, Sep. 2002.

274 Knights, M., New Technologies Add Zip to Rotomolding, PT, Jan. 2003.

275 Henkel Loctite, Rotomolding Release Suits Multiple Releases, MP, Oct. 2002.

276 Dorgham, M. & Rosato, D. V., Designing with Plastic Composites, Interscience Enterprises-Geneva, 1986.

277 Fussell, E., Sheding Light on Industrial Fiber Optics: A Strand of Hope for Fiber's Future, InTech, June 2003.

278 Daido Steel, Tool Steel Selection Software Targets Mold Making Startups, Modern Mold, 2000.

279 Davis, B. A., et al., Compression Molding, Hanser, 2003.

280 Krottner, V., Teach Yourself Polishing, Moldmaking Technology, Aug. 2000 & Reclaiming the Lost Art of Benching, Moldmaking Technology, Oct. 2000.

281 Mold Making, National Tool & Machining Assoc. General Literature, 2000.

282 Plute, M., The Basics of Tool Management, Moldmaking Technology, Jan. 2002.

283 Mennig, G., Mold-Making Handbook for the Plastics Engineer, 2nd Edition, Hanser, 1998.

284 Stoeckhert, K., Mold Making Handbook, 2nd Edition, Hanser, 1998.

285 The 2004 Corvette to Sport Carbon Fiber Hood, PN, June 2, 2003.

286 Smart Move: Forfour Targets U.S. Market (includes Plastics), PN, Jan.27, 2003.

287 Engineering a Composite Hyperyacht, RP, Dec. 2002.

288 Arctic (RP) Radomes, RP. Dec. 2002.

289 McConnell, V. P., Composites and the Fuel Cell Revolution, RP, Jan. 2002.

290 High-Performance Short-Fiber PP Rivals Long-Fiber Grades, MP, June 2003.

291 Purified Cellulose Fibers Show Promise in Reinforced Thermoplastics.

292 Marsh, G., Filling the Front-Line Training Gap, RP, Apr. 2002.

293 Marsh, G., MACT: A More Restrictive World for Boatbuilders, RP, Jan. 2002.

294 Rosato, D. V., Industrial Plastics in Materials Handling, International Mgm. Soc., Oct. 1985.

295 Jacob, A., Spray-up Offers Process Improvements, RP, Jan. 2002.

296 Soft Touch with Injection Compression Moulding, Polymotive, Feb. 2003.

297 Knights, M., Metal-Powder Injection Molding Moves Into Large Parts, PT, Feb. 2003.

298 Gaines, D., Metal Injection Molding, Job Shop Tech., Feb. 2003 and Aug. 2003.

299 Seeley, R. S., New Directions for Metal Molding, Job Shop Tech., Feb. 2003.

300 Cost Effective Infusion of Sandwich Composites for Marine Applications, RP, Dec. 2003.

301 Self-Reinforcing Thermoplastic is Harder, Stronger, Stiffer Without Added Fibers, PT, June 2003.

302 Engineering Resins (PPO) Extend their Reach, PT, June 2003.

303 Compounder Creates Flexible Process with Conveyor Line, Plastics Machinery & Auxiliaries, May 2003.

304 Combine Melts & Liquids of Different Viscosities, PT, Jan. 2003.

305 Compounding & Mixing Equipment, PT, June 2003.

306 Esposito, F., Compounders will Unveil an Assortment of Products (NPE), PN, May 12, 2003.

307 Flexible PVC, PE, Jun. 2002.

308 Coaker, A. W., Twentieth Century Ethics of Risks and Hazards in Business, SPE Vinyl Div. Newsletter, Jun. 1995.

309 Handbook for the Metalworking Industries, Gardner Publ., 2002.

310 Tobin, B., What is a Mold Worth? PM&A, Apr. 2003.

311 Mirman, I., A Model is Worth a Thousand Drawings, MoldMaking Tech., June 2003.

312 Molds and Tools, PT, June 2003.

313 Creehan, K. D., Developing Generalized Reverse Engineering Methodologies for Moldmaking, MoldMaking Tech., June 2003.

314 Top 20 Mold Makers, PN, Mar. 17, 2003.

315 Baranek, S. L., The International Special Tooling and Machining Association: A World Power, MoldMaking Tech., June 2003.

316 Bales, S. J., How to Locate the Right Polishing and Plating Vendor, MoldMaking Technology, Sep. 2002.

317 Kaszynski, J., Ensuring Mold Steel Polishability, MoldMaking Technology, Mar. 2003.

318 Ultrasonic Mould Cleaning, Polymotive, Feb. 2003.

319 Bales, S. J., Mold Preservation and Maintenance for Ultimate Productivity, MoldMaking Technology, Dec. 2001.

320 Rich, M. J., et al., Surface Cleaning of Mold Release Compounds, SPE ANTEC, 2002.

321 Dry-Ice Cleans Tools Fast, PT, Feb. 2002.

322 Knights, M., Unscrewing Molds Go Electric, PT, Sep. 2002.

323 Buyers' Guide to Molds, Dies, and Mold components, PE, Jan. 2003.

324 Monitoring Software Targets Family Molds, PT, May 2003.

325 Gorlich, R., et al., Designing 48 Individual Cavities in One Mold Plate, MoldMaking Tech., Feb. 2003.

326 Mold Design to Automation, IM, Feb. 2002.

327 Kaszynski, J., Choosing Thermally Conductive Tooling Materials, MoldMaking Tech., Aug. 2002.

328 Piscope, S., Milling Advances Increase Productivity, MoldMaking Tech., Jun. 2002.

329 Roy, S., et al., Options for Restoring Molds, MoldMaking Tech., Sep. 2002.

330 D-M-E Releases Survey on Mold and Die Industry, PE, Aug. 2002.

331 Dealey, B., What Could the Mold of Tomorrow be Like? MP, Feb. 2003.

332 Mold Designers Put the Web to Work, PT, Mar. 2003.

333 Software Checks Profile Die Designs, PT, May 2003.

334 CAD, CAM, & CAE Listing, PT, June 2003.

335 Lahti, G. P., Calculation of Pressure Drops and Outlets, SPE Journal, Jul. 1963.

336 Wohlers, T. and Et Al., Is CNC Machining Really Better Than RP/ MoldMaking Tech., June 2003.

337 Rapid Prototyping, Rapid Tooling, PE, Apr. 2002.

338 Rufo, M., Rapid Prototyping: Is It Common? MoldMaking Tech., Sep. 2002.

339 Rapid Prototyping System Produces Models with Improved Resolution, MP, Sep. 2002.

340 Gebhardt, A., Rapid Prototyping, Hanser, 2003.

341 Moore, S., Stereolithography Advances with Desktop System-Performance Resins, MP, June 2003.

342 Colvin, R., New Software Speeds and Simplifies Plastics Mold Design Works, MP, May 2000.

343 Shortt, M., Revenues Decline, Productivity Rises in Rapid Prototyping Industry, Job Shop Tech., May 2003.

344 Seeley, R. S., Rapid Prototyping: No Longer Just for Design Engineers, Job Shop Tech., May 2003.

345 Auxiliary Buyers Guide, PE, Mar. & July 2003.

346 Dryers/Hopper Loaders Buyer's Guide, PM&A, May 203.

347 Materials & Parts Handling Equipment, PT, June 2003.

348 Loading the Hopper, PE, Feb. 2003.

349 Heating & Cooling Equipment, PT, June 2003.

350 Cutting & Trimming Equipment, PT, June 2003.

351 Naitove, M., Joined-Arm Robot Handles Insert Loading and Part Removal, PT, June 2003.

352 New Source of Electronic Color-Matching Software, PT, May 2003.

353 Recycling & Scrap Equipment, PT, June 2003.

354 Salerni, C. M., Light-Cured Cyanoacrylates: An Adhesive Option for Medical device Assembly, MD&DI, Jun. 2002.

355 Ogando, J., Bonding Plastics 101, DN, Jan. 22, 2001.

356 Handbook of Plastics Joining, PDL, 1997.

357 Thompson, R., Adhesive Bonding, MP Encyclopedia, 1986–1987.

358 Grewell, D. A., Plastics and Composites Welding Handbook, Hanser, 2003.

359 Welding, Bonding, & Assembly Equipment, PT, June 2003.

360 Rohifs, T., Plastics Machining: Understanding the Basics, MD&DI, Apr. 2002.

361 Bogin, M., Working with Plastics Made Easier with Basic Machining Techniques, Job Shop Tech., May 2001.

362 Koenig, K. M., Fixturing & Routing Plastics with CNC Tooling, Plastics Machining & Fabrication, Winter, 1997.

363 Competitive Pressures Spur Shops to Tap EDM Automation, MP, Oct. 2002.

364 Leventon, W., Changes give a New Shape to Machining, MD&DI, Nov. 2002.

365 Shortt, M., Waterjet Cutting Produces Superior Quality, Significant Savings, Job Shop Tech., Aug. 2002.

366 Marsh, G., Composite Cutting Considerations, Reinforced Plastics, Nov. 2002.

367 Crosby, P., Get to Know Lasers and their Role in Plastics, PT, Jun. 2002.

368 Mapleston, P., Delcam Unveils Morphing, Automatic Machining Capabilities, MP, Aug. 2002.

369 Sudhakar, M., New Developments in High-Speed Machining Technology, MoldMaking Tech., Mar. 2003.

370 Cutting Tools Directory, MoldMaking Tech., Jan. 2003.

371 Lowrance, W. W., Of Acceptable Risk: Science and the Determination of Safety, Wm. Kaufmann Inc., 1976.

372 Sherman, L. M., How to Buy Universal Testing Machines, PT, Feb. 2003.

373 Supporting Composites Standardization: Part 1, RP, Dec. 2002.

374 ISO-9000 Part 2–Requirements, PE, Feb. 2003

375 ISO-13485 Splits fom ISO-9000, MD&DI, Feb. 2003.

376 Where is that Barrier: Multilayer Gauge, PE, Feb. 2003.

377 Rosato, D. V. Capt., All Plastic Military Airplane Successfully Flight Tested, Wright-Patterson AF Base, Ohio, 1944.

378 ASTM International Directory of Testing Laboratories, ASTM, 1999.

379 Hertzberg, R. W., et al., Fatigue Testing-Flaws Makes It Better, PW, May 1977.

380 Mordfin, L., Handbook of Reference Data for Nondestructive Testing, ASTM, 2002.

381 Sims, G., Composite Testing, Plastics Solutions International 2000.

382 Testing Against Trouble, World Plastics Technology, 2001.

383 Wigotsky,V., Plastics Testing, PE, Feb. 2002.

384 ASTM Book of Standards, Section 8: Plastics, Four Volumes, Annual Issues.

385 ASTM Dictionary of Engineering Science and Technology, 9th Ed., ASTM, 2000.

386 ASTM Index—Annual Book of ASTM Standards, ASTM Annual.

387 ISO Standards Compendium ISO 9000: Quality Management, 9th Ed., ASTM, 2001.

388 ISO Standards Handbook-Statistical Methods for Quality Control, 4th Ed., ASTM, 1995.

389 Sherman, L. M., Testing & Quality Control, PT, June 2003.

390 Rosen, R., Project Advisory Board: Improving Product Development Quality and Consistency, MD&DI, Feb. 2003.

391 Abbott, W. H., Statistics can be Fun, A. Abbott Publ., Chesterland, OH 44026.

392 Hannagan, T., The Use and Misuse of Statistics, Harvard Management Update, May 2000.

393 Mamzic, C. L., Statistical Process Control, ISA, 1995.

394 Rauwendaal, C., Statistical Process Control in Extrusion, Hanser1993.

395 General Motors Statistical Process Control Manual, GM-1693, GM Corp., 1984.

396 Western Electric Statistical Quality Control Handbook, Western Electric, 1956.

397 Ishikawa, K., Guide to Quality Control, Nordica International Ltd., Hong Kong, 1976.

398 Dow Sharpens Cutting Edge, Industry News, PE, Feb. 2002.

399 Leaversuch, R., Biodegradable Polyesters, PT, Sep. 2002.

400 Pryweller, J., U.S. Final Frontier for Biodegradable Resins, LN, Sep. 2, 2002.

401 Toloken, S., Agency May Alter Opinion of PVC Toys (Phthalate), PN, Sep. 30, 2002.

402 Rosato, D. V., Capt., Theoretical Potential for Polyethylene, USAF Materials Lab., WPAFB, 1944.

403 Self-Healing FRP, RP, Mar. 2001.

404 Self-Healing FRP, RP, Sep. 2002.

405 US Bridges Deficient, RP, Sep. 2002.

406 Resin Review: The Annual Statistical Report of the U.S. Plastics Industry, APC (formerly published by SPI as Facts and Figures in the U.S. Plastics Industry), Annual.

407 Rosato, D. V., Designing with Plastics, Rhode Island School of Design, Lectures 1987–1990.

408 Newborn, F., Cultivating a Spirit of Innovation, DN, Dec. 17, 2001.

409 Acquarulo, L. A., et al., Enhancing Medical Device Performance with Nanocomposite Polymers, MD&DI, May, 2002.

410 CAD/CAM Directory, MoldMaking Tech., May 2003.

411 Corelli, C., Rethink Your Business Strategy, MoldMaking Tech., May, 2003.

412 Johnson, C., et al., Quick and Below Budget, Industrial Computing, May 2003.

413 Moore, S., Global Demand Heats Up in High-Volume Markets, MP, Feb. 2003.

414 Toensmeier, P. A., Market Dynamics Redraw the Graph of Resin Supply, MP, Feb. 2003.

415 Recognize the Need, Generate the Lead, I-R World, Jan-Feb., 2003.

416 European Plastics Directory: Materials, Semi-Finished Products, Machinery, & Ancillary Equipment, Rapra, 2003.

417 Nypro Vision, Passion is Model of Success, PN, May 19, 2003.

418 Shapiro, J. K., Medical Device Reporting: A Risk-Management Approach, MD&DI, Jan. 2003.

419 Schmidt, M. W., Establishing Overall Risk for Medical Devices, MD&DI Feb. 2003.

420 In Pursuit of Failure, MD&DI, Feb. 2003.

421 Rosato, D. V., Environmental Effects on Polymeric Materials, Volumes 1 & II, Wiley, 1968.

422 Dow (Automotive) to Develop CBT Auto Structures, RP, June 2003.

423 Bregar. M., Monsanto Saw Potential of Michael Gigliotti, Plastics News, June 23, 2003.

424 Bregar, B., From War and Beyond, Rosato Has Write Stuff, Plastics News, June 23, 2003.

425 Pryweller, J., It's A First: KWS puts Paint in an (IM) All Plastic (Recycled PP) Can, Plastics News, June 23, 2003.

426 Mapleston, P., Compounds are Conductive or Not as Necessary, MP, Mar. 2003.

427 Rosato, D. V., Non-Woven Fibers in Reinforced Plastics, Ind. Engr. Chem., 54,8. 30–37, Sep. 1962.

428 Bregar, B., Latest Husky Injection Press Competes its Hylectric Line, Plastics News, June 23, 2003.

429 Improving the Efficiency of Electrical Safety Testing, Compliance Engr., Annual, 2003.

430 Injection Molding Machines Buyer's Guide, Plastics Auxiliaries & Machinery, June 2003.

431 Bregar, B., Twinshot Goes Beyond the Spirex Booth, Plastics News, Jun. 24, 2003.

432 Simulation Software Gains New Capabilities (warp, etc.), PT, Fib. 2003.

433 Kingberg, P. M., Facing Water Management Issues that are Critical in Processing Settings, Plastics Auxiliaries & Machinery, June 2003.

434 Extrusion Line Changes Dimensions at Button's Touch, Plastics Auxiliaries & Machinery, June 2003.

435 Blow Molding Technical Papers, SPE Annual, Oct. 14–15, 2003.

436 Extrusion with No Confusion (Harrel Inc.), PE, June 2003.

437 Espoito, F., Bayer Calls Thermoformable Nylon 'Next Syep', Plastics News, Jun. 24, 2003.

438 McNulty, M., PU Producers Tackle Key Issues, Plastics News, Jun. 24, 2003.

439 Producing Fibers that Mimic Spider Silk, MD&DI, June 2003.

440 Boron-Free Glass Fibres-the Trend for the Future, RP, June 2003.

441 Technology Update: Prepregs, RP, June 2003.

442 Spray Equipment Adapts for Success, RP, June 2003.

443 Focused on Foam: Sentinel Producys Corp., PT, Jul 2003.

444 Okamoto, K. T., Microcellular Processing, Hanser, 2003.

445 Composites Certification Program Hits 1000 Mark, PT, July 2003.

446 Automotive PC Glazing System Makes Debut at NPE, PT, July 2003.

447 New Welding Technologies, PT, July, 2003.

448 Grewell, D. et al., Plastics and Composites Handbook, H anser, 2003.

449 Clarity a Big Shot: Aircraft Canopy, PT, July 2003.

450 Self-Reinforcing Thermoplastic is Harder, Stronger, Stiffer Without Added Fibers, PT, July 2003.

451 HDPE for Pipe Gets Top Performance Ratings: 100 yr Pressure Rating, PT, July 2003.

452 Buyer's Guide: A Directory of Moldmaking Products and Services and Their Suppliers, MoldMaking Technology, July 2003.

453 Avoid Common Mold Set-Up Mistakes, PT, July 2003.

454 New Generation DMA (dynamic mechanical analysis), PE, June 2003.

455 Testing Equipment Buyers' Guide, PE, June 2003.

456 Test Equipment and Software (EMC, ESD, Telcom, Environmental, and Safety), Compliance Engr., Annual, 2003.

457 Testing and Services, Compliance Engr., Annual, 2003.

458 Advances in Medical Plastics, MD&DI, June 2003.

459 Pryweller, J., Mold-Masters Cautious on Road to China, Plastics News, Jun. 24, 2003.

460 Product Safety Standards, Compliance Engr., Annual, 2003.

461 Valero, G., Shifting Paradigms, MP, July 2003.

462 Blanco, A., Functional and Aesthetic: Acetal, PE, July 2003.

463 Making Smarter Plastics, MD&DI, July 2003.

464 Metal Molding Shapes Up As Appealing Market, MP, Aug. 2003.

465 Boeing Opts for Composites for 7E7, RP, July/Aug. 2003.

466 Carbon Fibre SMC Halves Weight of Automotive Parts, RP, July/Aug. 2003.

467 Prepreg Qualification Scheme, RP, July/Aug. 2003.

468 SPI Reaches Tentative Pact on PFOA Tests, PN, July 14, 2003.

469 Technology Update: Compression Moulding, RP, July/Aug. 2003.

470 Snyder, M. R., Size Reduction Equipmenet, PM&A, July/Aug. 2003.

471 Deligio, T., Structural Plastics Combines Form and Function: RIM, PM&A, July/Aug. 2003.

472 Piezoelectric Sensor Suits Small Mold Applications, PM&A, July/Aug. 2003.

473 Bayer Polymers Focuses on Profitability, RP, July/Aug. 2003.

474 Leventon, W., Hemocompatible Coatings for Blood-Contacting Devices, MD&DI, Aug. 2003.

475 Esposito, F., Toll Compounders Forming Global Alliance, PN, July 28, 2003.

476 NPE New Technology Wrap-Up: Injection, Extrusion, Blow, Thermoforming, PT, Aug. 2003.

477 Rotomolders Learning the Language of Automation, MP, Aug. 2003.

478 Manufacturing Promotes Growth, PN, July 28, 2003.

479 Sloan, J., The Value of Making Things: Divest in Manufacturing and Trade Stuff, MP Aug. 2003.

480 Cermak, B., Growing Strong: Save American Manufacturing, MoldMaking Tech., Aug. 2003.

481 Panagas, J., Making Plastic Parts in Five Weeks: Casting in silicone rubber molds, MoldMaking Tech., Aug. 2003.

482 Bassi, G. P., Designing Molded Products Just Got Simpler, MoldMaking Tech., Aug. 2003.

483 Brockman, D., et al., How to Choose the Right Plated Coating for Improved Mold Performance, MoldMaking Tech., Aug. 2003.

484 Davis, B., et al., Compression molding, Hanser, 2003.

485 U.S. PET Beverage Container Market, PN, Aug. 18, 2003.

486 Leventon, W., Material Progress Toward Better molded Parts, MD&DI, Mar. 2003.

487 Scherr, J., Flow Analysis Gets it Right the First Time, PT, Apr. 2003.

488 Rosato, D. V., et al., Filament Winding-Its Development, Manufacture, Applications, and Design, Wiley, 1064.

489 S. T. Peters, et al., Filament Winding Composite Structure Fabrication. Publisher Society for the Advancement of Material and Process Engineering (Covina, CA, USA), 1991.

490 Knights, M., Hot Runnners, PT, Sep. 2003.

491 New Single-Site Technology Produces LLDPEs for Film, Injection, and Rotomolding, PT, Sep. 2005.

492 Muller, J. et all., Ten Myths About Gear Lubrication, SPE Extrusion Division Newsletter, Vol. 29, No. 3, Winter 2003.

Chapters 1 to 3

Murphy, J., Additives for Plastics Handbook, 2nd Edition, Elsevier Advanced Technology, 2001.

Chapter 15

Murphy, J., Reinforced Plastics Handbook, 2nd Edition, Elsevier Advanced Technology, 1998.

Biron, M., Thermosets and Composites, 2nd Edition, Elsevier Advanced Technology, 2003.

Campbell, F. C., Jr., Manufacturing Processes for Advanced Composites, 2nd Edition, Elsevier Advanced Technology, 2003.

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